U.S. DEPARTMENT OF COMMERCE

PB80-167075

Environmental Protection Agency (EPA) Evaluation of Water Plant Lime Sludge in an Industrial Boiler FGD (Flue Gas Desulfurization) System at Rickenbacker AFB

Cottrell Environmental Sciences
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Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Nov 79

U.S. Department of Commerce
National Technical Information Service
NTIS.

PB80-167075

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-79-247
November 1979

EPA

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Interagency Energy/Environment R&D Program Report

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TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA-600/7-79-247	2.	3. RECIPIENT'S ACCESSION NO. PB80 167075
4. TITLE AND SUBTITLE EPA Evaluation of Water Plant Lime Sludge in an Industrial Boiler FGD System at Rickenbacker AFB		5. REPORT DATE November 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert J. Ferb		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Cottrell Environmental Sciences P.O. Box 1500 Somerville, New Jersey 08876		10. PROGRAM ELEMENT NO. EHE624 11. CONTRACT/GRANT NO. Interagency Agreement D5-0718
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 9/78 - 2/79 14. SPONSORING AGENCY CODE EPA/600/13
15. SUPPLEMENTARY NOTES IERL-RTP project officer is John E. Williams, Mail Drop 61, 919/541-2483.		

16. ABSTRACT The report gives results of a September 1978-February 1979 test program to evaluate lime water softening waste sludge as an alternate reagent for a flue gas desulfurization (FGD) system on an industrial boiler at Rickenbacker Air Force Base, Ohio. The study also included assessing the availability of the material, designing a system to handle and feed the material, and comparing the economics with conventional lime and limestone reagents. The tests showed that such material worked very well as a reagent and was comparable to lime performance during earlier tests. At SO2 removal efficiencies of up to 80%, utilization exceeded 95%. The study showed that as much as 4-5 million tons/year of the material may be available, much of it in the Midwest U.S. where large deposits of high sulfur coal and a heavy population of industrial plants are located. Estimates indicated that use of water softening sludge in a typical industrial FGD system results in substantially lower annual operating costs compared with either lime or limestone.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Flue Gases Desulfurization Calcium Oxides Sludge Water Softening	Pollution Control Stationary Sources	13B 21B 07A,07D 07B
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified 20. SECURITY CLASS (This page) Unclassified	21. NO. OF PAGES 22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/7-79-247

November 1979

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Interagency Agreement No. D5-0718
Program Element No. EHE624

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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
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ABSTRACT

A test program, which evaluated the use of lime sludge (a waste product from water treatment plants) as a reagent for SO_2 removal in an industrial sized flue gas desulfurization system, surveyed potential sources of lime sludge supplies, developed a lime sludge handling system and determined the economics of lime sludge utilization was completed. The program was started in September 1978, tests were conducted at Rickenbacker RAFB in Ohio and work was completed on the program in February 1979.

The results of the program demonstrate that lime sludge is an ideal reagent for flue gas desulfurization. Sources of lime sludge exist in areas where flue gas desulfurization is practiced and the cost of using lime sludge is significantly lower than that for conventional reagents such as lime and limestone.

Lime sludge reacts similarly to lime as FGD reagent up to stoichiometric ratio of 0.8. At SO_2 removal efficiencies up to 80% lime sludge utilization exceeded 95%.

Numerous sources of lime sludge are located in midwestern states where large deposits of high sulfur coal are found. A limited survey indicates that over 400,000 TPY of lime sludge is available. Data contained in the Lime Chapter of the Bureau of Mines 1977 Mineral Year Book indicates that as much as 4 - 5,000,000 TPY may be available.

Lime sludge handling facilities for a typical industrial sized FGD system cost approximately $100,000 to install and $55,000 per year to operate. The use of lime sludge in a typical industrial FGD system results in annual savings of $63,000 and $22,000 over lime and limestone respectively. If lime sludge disposal credits are included an additional annual saving of $50,000 can be realized.

ACKNOWLEDGEMENTS

The cooperation of the Base Civil Engineering Staff of Rickenbacker AFB, is greatly appreciated. Especially that of James B. Rasor, Associate Base Civil Engineer, and Herbert Robinson, Scrubber Technician.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BTU	British thermal unit
cm	centimeter
d	day
fps	feet per second
gal	gallon
gpm	gallon per minute
j	joule
ft	feed
hr	hour
in	inch
k	kilo
l	liter
lb	pound
mi	miles
m	meter
mg	milligrams
mm	million
ppm	parts per million
wt	weight
sec	second
I.D.	inside diameter
T	ton
TPY	ton per year
Mg	megagram
y	year

SECTION 1

INTRODUCTION

This program has demonstrated that it is technically and economically feasible to use lime sludge as a reagent in Flue Gas Desulfurization (FGD) Systems. This result offers opportunities to alleviate two significant environmental problems, one in solid waste disposal and one in air pollution control.

Among the major problems facing operators of public drinking water supply facilities is the disposal of solid wastes from water treatment plants. Among the wastes produced is lime sludge which is formed when lime is used for softening water supplies prior to distribution. If wide scale utilization of lime sludge in FGD systems were undertaken, it would virtually eliminate the need for lime sludge disposal.

A further problem of FGD systems themselves is the cost of suitable SO_2 scrubbing reagents. The use of lime sludge in an FGD system is significantly less expensive than the use of lime or even limestone.

In order to understand the main purposes of this program a brief description of a typical water softening process where lime sludge is produced is necessary.

Lime sludge is produced when lime is used to remove calcium and magnesium hardness from drinking water supplies. These cations which are usually present with bicarbonate and carbonate anions are removed by the addition of lime in the form of calcium hydroxide. The overall process, as illustrated below for calcium bicarbonate and magnesium carbonate,

$$Ca^{++} + 2HCO_3^{--} + Ca(OH)_2 \rightarrow 2CACO_3 + H_2O$$

$$Mg^{++} + CO_3^{--} + Ca(OH)_2 \rightarrow Mg(OH)_2 + CaCO_3$$

results in the precipitation of calcium carbonate and magnesium hydroxide from the water. This precipitate, the lime sludge, is separated from the water and accumulated in lagoons or ponds. Typically the lime sludge which is composed of 5 to 15 micron particles, contains 85 to 95% calcium carbonate and small amounts of magnesium hydroxide. These physical and chemical attributes make lime sludge an ideal reagent for use in FGD processes.

There is one further factor which contributes signficantly to the potential usefulness of lime sludges. This type of water softening process is practiced at many locations

in the midwest where there are large local deposits of high sulfur coal. In these areas flue gas desulfurization is almost essential to permit expanded use of these fuels.

The work described in this report is a continuation of an earlier program conducted at Rickenbacker AFB in Ohio under the sponsorship of the USEPA[1].

The primary objectives of this program are:

- o Determine the performance of an FGD system when using water plant lime sludge.
- o Determine the location of major sources of lime sludge
- o Determine the feasibility of handling lime sludge.
- o Determine the economics of using lime sludge as a reagent in FGD systems.

Each of these objectives are dealt with in detail in subsequent sections of this report.

---

(1) EPA Evaluation of Bahco Industrial Boiler Scrubber System at Rickenbacker AFB, EPA-600/7-78-115 June 1978.

SECTION 2

SCRUBBER TESTS

The performance of an FGD system is dependent upon many factors, reagent performance is one of the most important. This portion of the program, the scrubber tests, demonstrated that lime sludge both from materials handling and reagent reactivity points of view is a suitable reagent for FGD systems.

Since the tests were conducted in an FGD system designed to handle solid reagents, some system modifications were necessary. These modifications are described first, the test procedures are described next and finally the test results are presented.

R-C/BAHCO SCRUBBING SYSTEM

The FGD system at Rickenbacker Air Force Base (RAFB) which was used for this test program is described in detail in the previously cited EPA report[1]. For this program the system was modified to facilitate the use of lime sludge obtained from the City of Columbus Morse Road water treatment plant.

The test program consisted of an essentially continuous run designed to determine SO_2 removal at two levels of stoichiometry.

System Description

Hot flue gas from each of the Heat Plant generators at RAFB is passed into a common flue which contains a bypass stack. This stack allows makeup air to be drawn into the system at low load to maintain efficient operation of the mechanical collector and scrubber. Flue gas, with or without makeup air, is passed through a mechanical collector to remove coarse particulate matter before entering the booster fan.

This fan forces flue gas into the first stage of the scrubber where it is vigorously mixed with scrubbing slurry in an inverted venturi. In this stage, flue gas is cooled to its adiabatic saturation temperature and SO_2 and particulate are scrubbed from the gas. This partially scrubbed gas rises to the second stage where it is contacted with slurry containing fresh alkali to complete the required SO_2 and particulate removal. Gas from the second stage enters a cyclonic mist eliminator where entrained slurry droplets are separated from the gas by centrifugal force to produce an essentially droplet-free effluent.

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Pebble lime from a storage silo is slaked and added directly to the slurry in the lime dissolving tank, ground limestone can also be used. The resulting fresh lime mixture is pumped to the second stage (upper) venturi to treat the flue gas stream. The slurry flows by gravity from the second stage to the first stage where it contacts hot flue gas entering the scrubber. This countercurrent flow arrangement results in high SO_2 removal and efficient reagent usage.

Spent slurry flows by gravity from the first stage of the scrubber to the dissolving tank. Part of the spent stream leaving this stage is diverted to the thickener where the slurry is concentrated to 35 to 40% solids. Overflow from the thickener returns to the dissolving tank and the underflow is pumped to a Hypalon-lined sludge pond near the Heat Plant.

The scrubbing system prior to being modified for the test program is illustrated in Figure 2-1.

The following changes were made to permit testing with lime sludge:

- The slurry feed to the thickener was diverted directly to the sludge pond. A spare sludge pump was used for pumping this material to the pond.
- A portable gasoline driven pump was used to unload lime sludge from tank trucks into the thickener. The thickener served as a feed tank.
- A recirculation line which ran from the bottom of the thickener to the lime dissolving tank was installed. At the dissolving tank a short takeoff line with a manual control valve was installed to feed lime sludge into the dissolving tank.

These changes were accomplished by adding several quick disconnects into existing lines along with some new lengths of hose. Figure 2-2 illustrates the system as modified for the tests.

The use of quick disconnects allowed the system to be returned to normal operation after the test work was completed with a minimum of downtime.

System Operation

With the above modifications, the system was operated in the following manner.

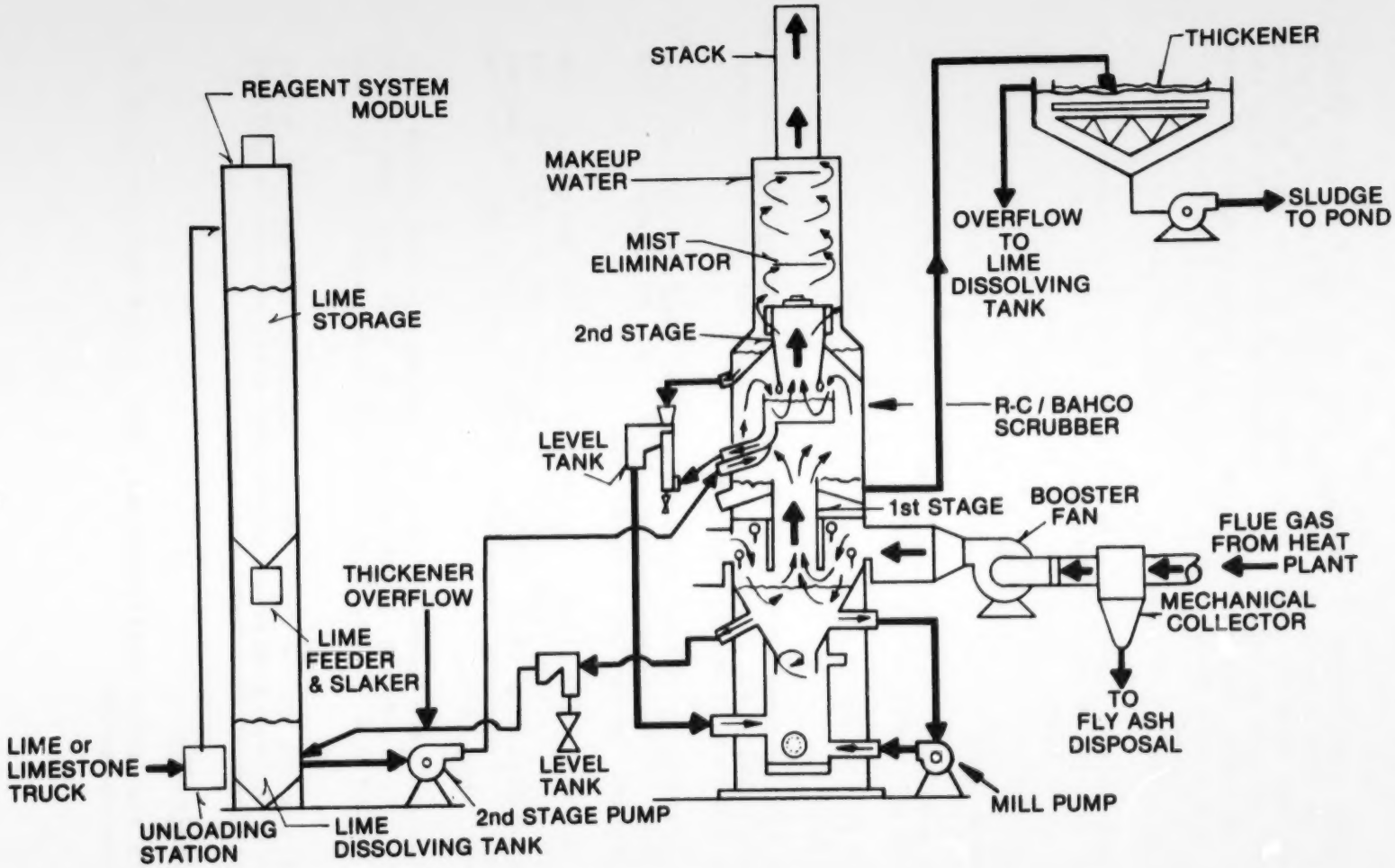

Figure 2-1: R-C/Bahco Scrubber System Flow Diagram

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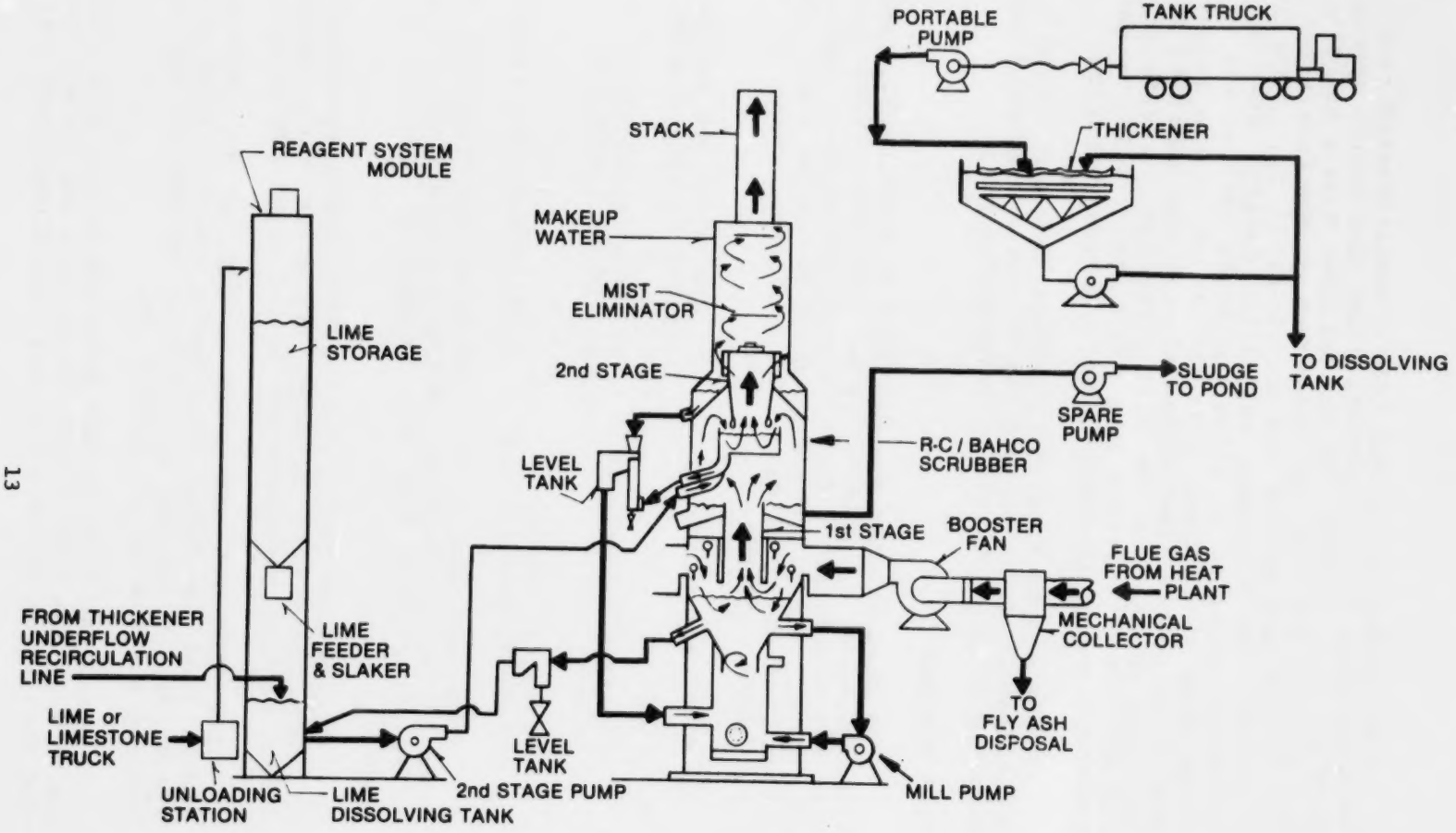

Figure 2-2: R-C / Bahco Scrubber System Flow Diagram as Modified for the Test Program

Lime sludge was loaded into a compartmented tank truck at the Morse Road water treatment plant and hauled approximately 32 km (20 mi.) to RAFB. At the scrubber site a gasoline driven self priming mud pump was hooked up to the tank trunk and the lime sludge was pumped via a 7.6 cm (3 in.) hose into the thickener. The thickener was filled during the day with sufficient material to allow operation through the night. A sludge pump which draws from the bottom of the thickener was used to circulate lime sludge through the modified flow loop described above. At the dissolving tank, a side stream was bled off the circulating loop via a manual valve to maintain a predetermined pH in the R-C/Bahco scrubbing system.

Spent slurry from the scrubber that was normally fed to the thickener prior to pumping to the sludge pond was pumped directly to the pond via a spare sludge pump.

TEST PROGRAM

The test program was designed to measure SO_2 removal efficiency over a range of lime sludge-SO_2 stoichiometries. This was accomplished during a continuous run of approximately five days. All significant system variables other than stoichiometries were maintained at preferred levels for the test run. These included:

Total gas volume	59,000 to 76,000 Nm^3/hr (35,000 to 45,000 SCFM)
Slurry Circulation Rate	8,300 to 9,100 l/min (2,200 to 2,400 gpm)
First and Second Stage Pressure Drops	1.74 to 2.49 KPa (7-10 in W.C.)

Data and samples were taken at approximately four hour intervals during testing. A typical data sheet and a summary of scrubber test data are located in Appendix C of this report.

In addition to SO_2 removal data, handling characteristics of lime sludge and scrubber operation were observed both during routine operation and during upset conditions.

The test run was begun on October 27, 1978 with lime sludge from the Morse Road water plant. Lime sludge feed system piping changes were made on October 27 and 28, actual testing was started on October 28.

Dissolver tank pH was selected as the main variable for control of the lime sludge feed; this choice was contrary to the initial selection of direct lime sludge feed rate control.

This change was made on the basis of the very rapid response of scrubber system pH to changes in lime sludge feed rate as observed on October 27th.

Two levels of pH were selected for testing, the first was a pH of 4.5 which corresponded to a lime sludge-SO_2 stoichiometry of about 0.6 and the second a pH of 6.0 which corresponded to a stoichiometry of approximately 0.8. These levels of pH were selected on the basis of experience with lime gained during the prior test work. Normal system load variations, as previously experienced, produced further lime sludge-SO_2 stoichiometry variations above and below the levels selected.

A histogram, of SO_2 removal efficiency and pH versus time, Figure 2-3, illustrates system SO_2 removal efficiency and pH during the test program. The low pH portion of the run produced moderate SO_2 removal efficiency i.e. 50% to 70% while the higher pH produced SO_2 removals of 75% to 85%. These results were similar to those observed during earlier tests with lime when operating at SO_2 concentration in the 300 to 500 ppm range[2].

During the pretest period on October 27 an interesting phenomenon occurred in the dissolving tank. The lime sludge feed to the dissolving tank was interrupted and a sharp drop in pH occurred. The feed was resumed at a high rate to bring the pH up quickly. When this was done there was a rapid evolution of CO_2 gas from the reaction of calcium carbonate in the lime sludge with the acidic slurry in the scrubber. This produced a voluminous and persistent foam which had to be disperesed with a hose.

This foaming occurred again during an upset in the test program on the morning of October 30th. At this time the lime sludge supply had been totally depleted after an overnight run and the feed was resumed at a high rate after the first tank truck was unloaded in the morning. This penomenon in and of itself does not interfere with operation of the system, however, otherwise unnecessary operator time is required to disperse the foam.

With a permanent lime-sludge feed system, including automated pH control, this type of pH excursion followed by excessive lime sludge feed would not be likely to occur.

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[2] These results are reported in the reference cited in footnote (1).

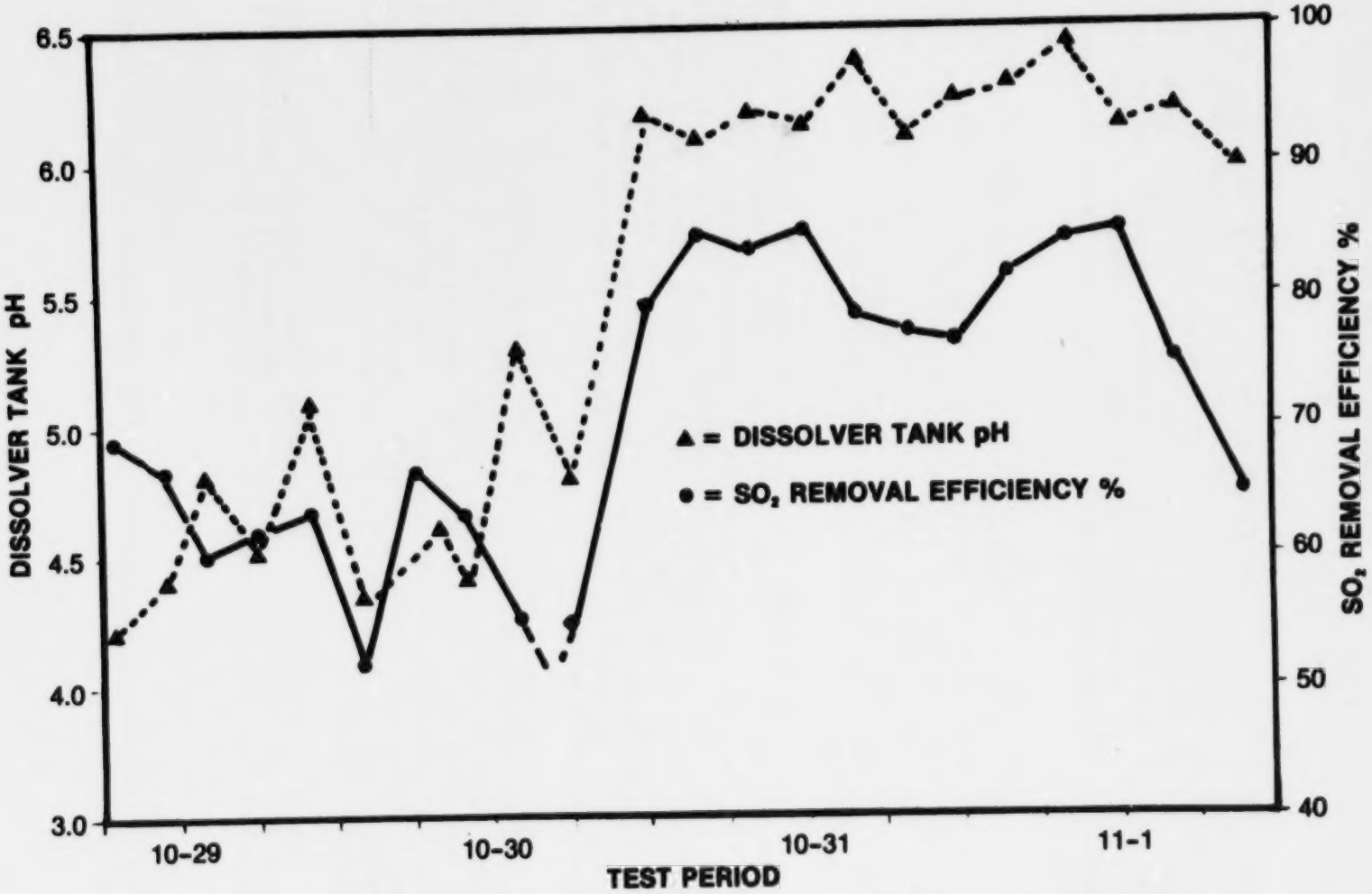

Figure 2-3 DISSOLVER TANK pH AND SO_2 REMOVAL EFFICIENCY DURING THE TEST PERIOD

TEST RESULTS

The results of the scrubbing tests indicate that lime sludges are ideal reagents for use in FGD systems. This is true both with regard to their reactivity and with regard to their handling. Conventional equipment is capable of handling lime sludge.

During the testing 22 complete data sets and samples were taken more or less at four hour intervals. In accordance with the scope of work, nine data sets were selected at random from these for complete evaluation. The results from these nine tests are summarized in Table 2.1.

The same approach that was used in earlier work, non-steady state testing, was employed during this program. This approach is necessitated by the inherent variability in boiler load at RAFB. Load variations cycled in a time span similar to the scrubbing system's 12 to 24 hour residence time. This fact rendered steady state testing impossible.

The effect of this situtation was minimized by taking data and samples and subsequently analyzing them to determine the actual levels of lime sludge stoichiometry during the test period. As indicated, this approach does not permit precise regulation of variables; however, a full range of lime sludge SO_2 stoichiometry was investigated and the SO_2 removal efficiencies observed covered the range of interest for most industrial FGD systems.

SO_2 Absorption

SO_2 removal efficiency ranged from about 52% to nearly 85% during the test program.

During the early part of the run, when the system pH was kept in the 4 to 5 range, SO_2 removal efficiency averaged 58.48%, lime sludge-SO_2 stoichiometry averaged 0.59 and alkali utilization was nearly complete at 98.58%.

During the latter part of the test run when the system pH was maintained in the 6.0 to 6.5 range, SO_2 removal efficiency averaged 79.34%, lime sludge-SO_2 stoichiometry averaged 0.84 and alkali utilization was 94.36%. The high levels of SO_2 removal and alkali utilization observed during these tests are very similar to those observed for lime during earlier test work cited above.

The lime sludge data is compared to earlier lime test data in Figure 2-4. As illustrated by the figure, the results obtained from lime sludge are indistinguishable from those for lime up to a stoichiometry of about 0.8.

TABLE 2.1
SUMMARY OF SO_2 REMOVAL TEST AT
RAFB USING LIME SLUDGE

Date/Time Test		SO_2 % Removal Efficiency	Alkali/SO_2 Stoichiometry	pH	Reagent Utilization %	% of Total $CaCO_3$	Alkali* $Ca(OH)_2$
10/28/78	19:10(A)	66.5	0.686	4.2	96.5	93.7	6.3
10/29/78	3:10(B)	60.3	0.617	4.4	97.8	89.7	10.3
10/29/78	14:10(C)	51.8	0.518	4.35	100.0	100.	-
10/20/78	2:10(D)	55.3	0.553	5.3	100.0	89.8	10.2
10/30/78	20:00(E)	82.2	0.822	6.2	100.0	89.8	10.2
10/31/78	4:10(F)	78.6	0.848	6.40	91.8	92.6	7.4
10/31/78	12:00(G)	76.5	0.795	6.25	96.2	92.5	7.5
10/31/78	20:00(H)	84.4	0.943	6.45	88.6	100.	-
11/1/78	4:00(I)	75.0	0.788	6.2	95.2	92.6	7.4

	Average SO_2 Removal Efficiency %	Average Stoichiometry	Average Alkali Utilization
Tests A thru D	58.48	0.59	98.58
Tests E trhu I	79.34	0.84	94.36

* These values are expressed in mole percent and alkali listed under $Ca(OH)_2$ is a combination of $Mg(OH)_2$ and $Ca(OH)_2$ $Ca(OH)_2$ reported as $Ca(OH)_2$

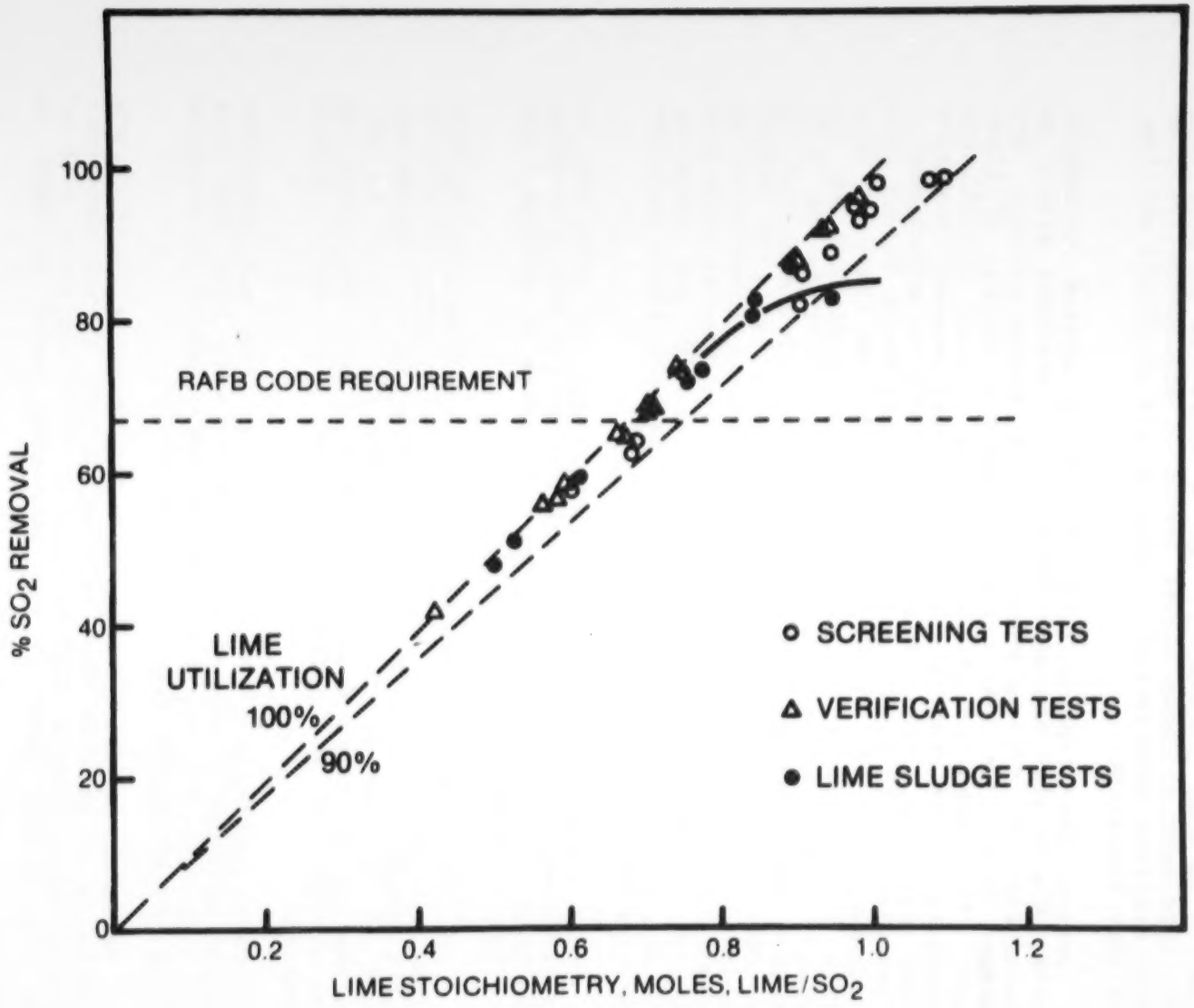

Figure 2-4: SO_2 REMOVAL EFFICIENCY AS A FUNCTION OF LIME AND LIME SLUDGE STOICHIOMETRY.

When the lime sludge data is compared to earlier limestone SO_2 removal data as in Figure 2-5, the tendency for decreasing lime-sludge utiliztion at higher levels of stoichiometry is more pronounced. It is important to note however, that even at these higher levels of stoichiometry, lime sludge exhibits substantially higher levels of alkali utilization than limestone.

During the testing, the scrubbing system exhibited another distinctive characteristic, i.e., scrubber slurry pH sensitivity to stoichiometry. This characteristic was observed in earlier lime tests but was not typical of limestone. This behavior is thought to be related to both the reactivity of the reagent and to the actual reagent inventory in the scrubbing system. High pH sensitivity to stoichiometry is associated with highly reactive reagents which do not tend to accumulate in the system. Thus, with lime there is very little in process inventory and nominal buffering in the system. Limestone on the other hand, tends to be less reactive and substantial in process inventories are normally present. This limestone reagent inventory tends to dampen changes in the system making the pH somewhat insensitive to changes in stoichiometry. The pH and stoichiometry data from the lime sludge tests as well as earlier lime and limestone data are plotted in Figure 2-6 to illustrate their relative characteristics.

This lime-like behavior of lime sludge, in spite of its approximately 90% calcium carbonate content, probably results from both it's calcium and magnesium hydroxide content, and more importantly, from its particle size.

The lime sludge tested at RAFB had the size distribution illustrated in Figure 2-7 with a mass median particle size of approximately 6-7 microns. This size distribution, which was found to be typical for lime sludges[3], results in approximately ten times as much surface area for reaction as the same weight of a typical 74 micron (200 mesh) ground limestone.

This combination of fine particle size and hydroxide content produces a reagent which behaves very much like lime with regard to SO_2 removal capabilities, reagent utilization and system pH sensitivity to stoichiometry.

Research-Cottrell has performed in house studies of the reactivity of various high calcium content ground limestone with dilute sulfurous acid solutions. When the reactivity of the lime sludge used in the scrubbing tests at RAFB is

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(3) See Section 3.0 of this report Characteristics of Lime Sludge

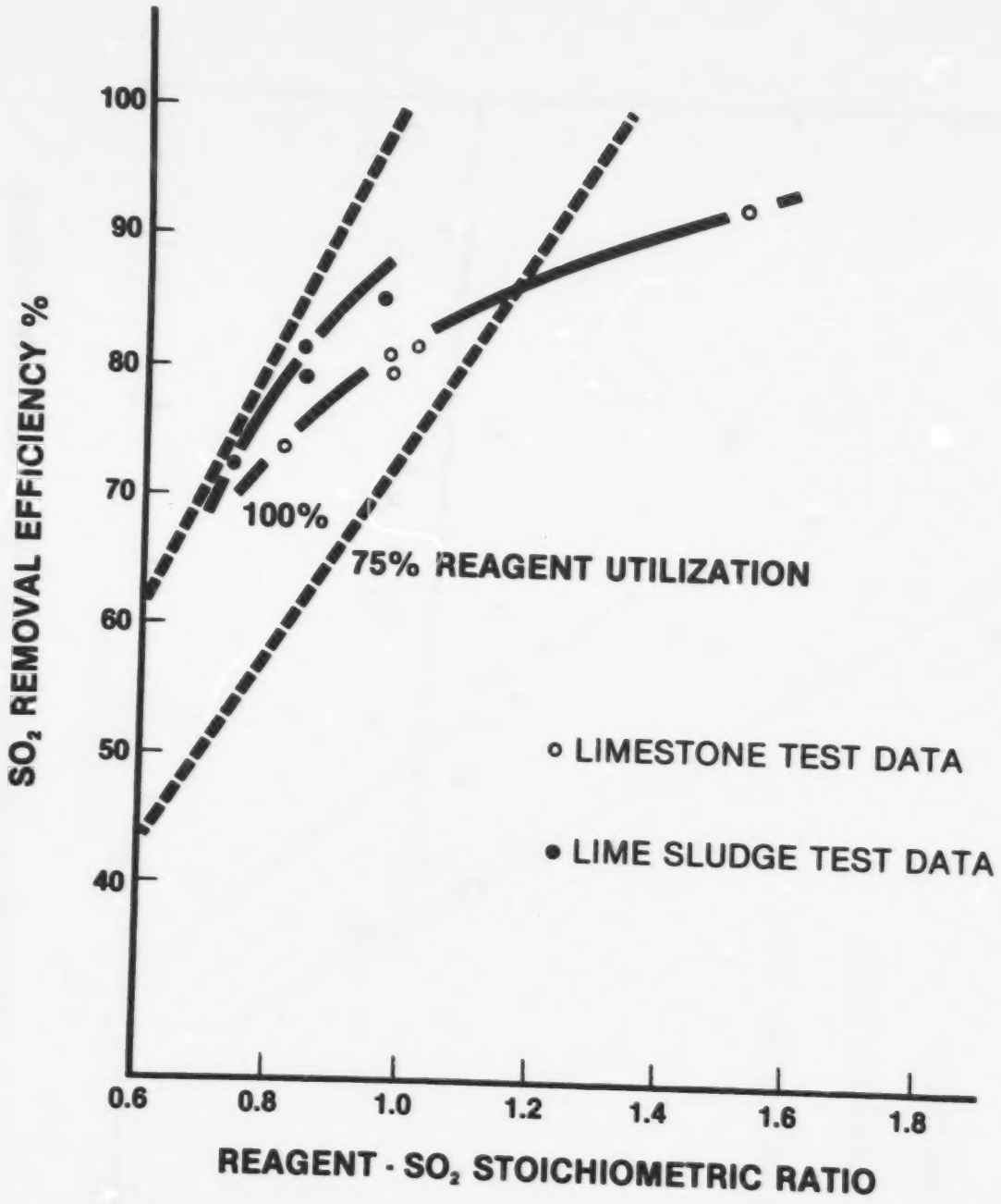

Figure 2-5: SO_2 REMOVAL EFFICIENCY AS A FUNCTION OF LIMESTONE and LIME SLUDGE STOICHIOMETRY

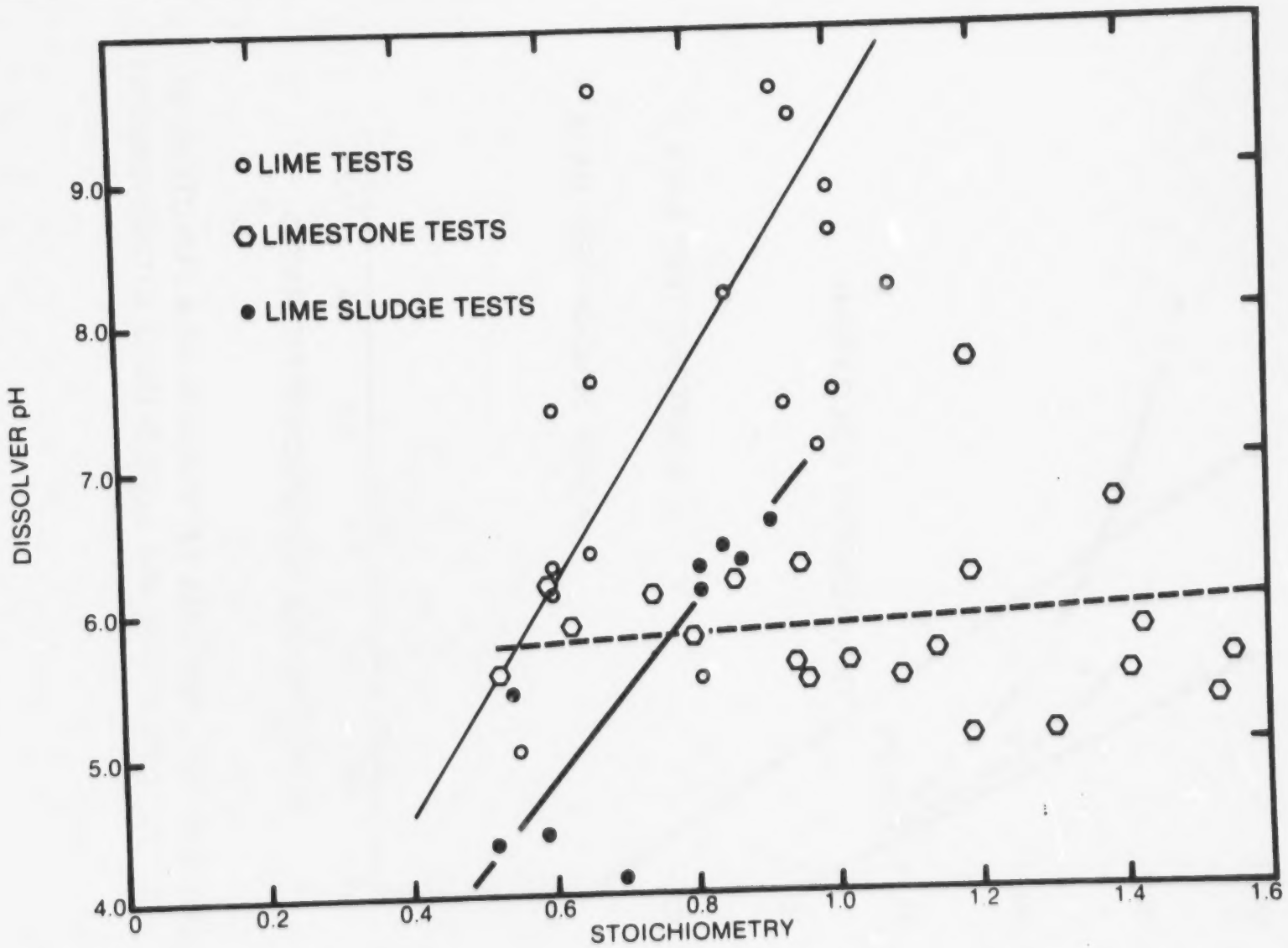

Figure 2-6: THE EFFECT OF LIME, LIMESTONE AND LIME SLUDGE STOICHIOMETRY ON DISSOLVER pH.

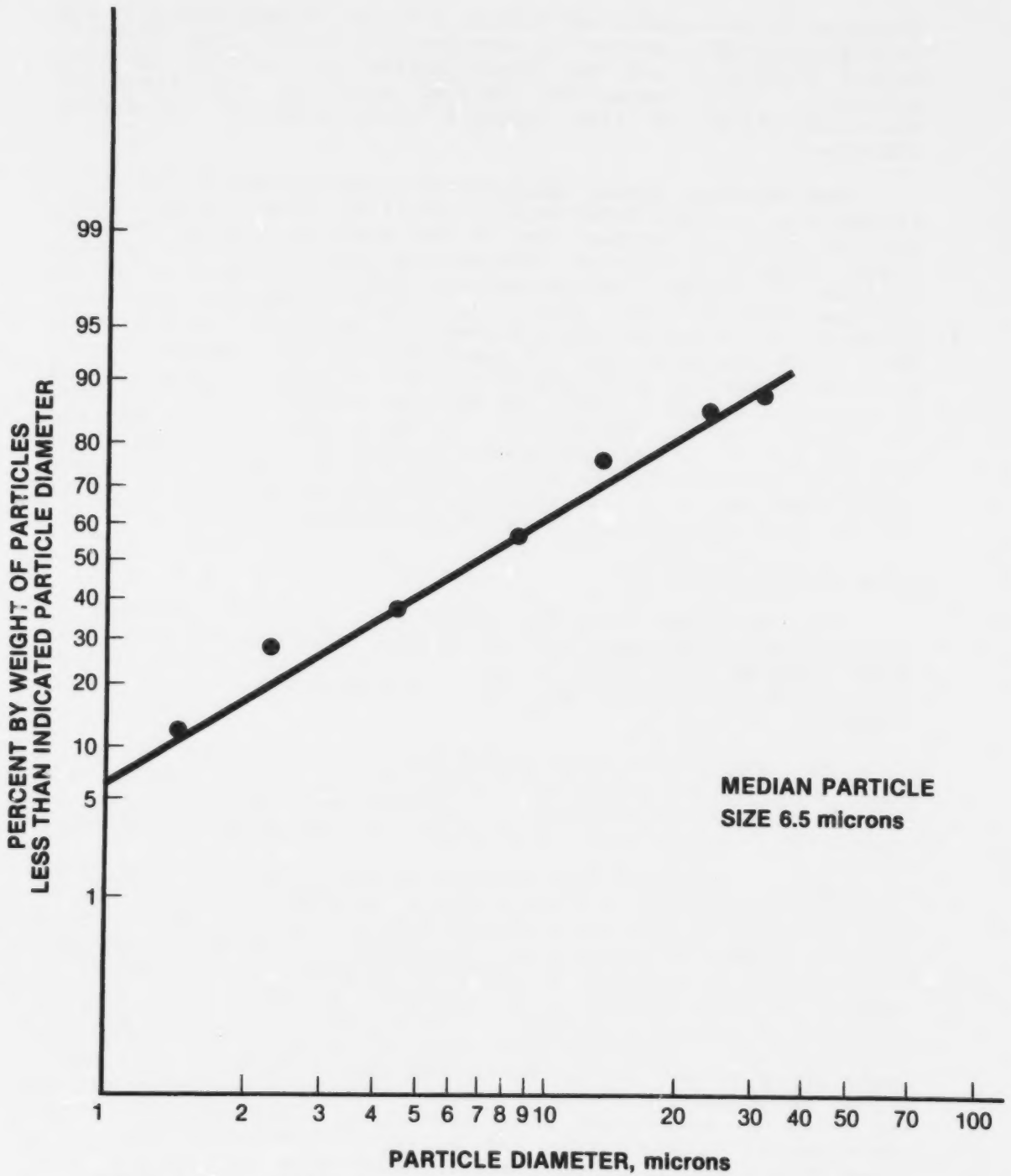

Figure 2-7 WATER PLANT SLUDGE SIZE DISTRIBUTION

compared to this data (see Figure 2-8) it is apparent that the initial rate of reaction is substantilly faster than that for ground limestone and the final degree of reaction is also greater. This comparison further confirms the lime-like characteristics of lime sludges when compared to ground limestone.

The scrubber slurry analyses data summarized in Table 2.2 illustrates another interesting result of these tests regarding the chemical composition of the scrubber slurry samples. These samples contained substantial quantities of calcium sulfate as gypsum (approximately 88%) with little or no calcium sulfite (less than 1%). This indicates that substantial oxidation of the absorbed SO_2 occurred. Earlier test work with limestone at the same 300 to 500 ppm SO_2 level produced a similar high gypsum content slurry. An analysis of a typical limestone slurry as well as one when lime was used is illustrated in Table 2.3, in which the calcium sulfite content was 54.5% and the gypsum content was only 33.4%. The slurries produced during these tests are very similar to limestone slurries, i.e., predominantly calcium sulfate, in spite of the lime-like characteristics of the lime sludge.

Lime Sludge Handling

The handling of lime sludge is a critical element in evaluating its suitability as an FGD reagent. During this test program lime sludges were successfully loaded, transported and unloaded using a tank truck and conventional slurry pumps.

The tank trucks were loaded with lime sludge at the Morse Road water plant via their lime sludge pumps. After the twenty mile trip to RAFB the trucks were unloaded without agitation via a gasoline engine driven self priming mud pump.

After transport and unloading into the thickener some settling occurred. During testing periodic measurements of the thickener under flow specific gravity were made. This data is listed in Table 2.4. In addition, the solids concentration was determined on selected samples. Lime sludges in excess of 30% solids were handled routinely with an air operated diaphragm pump and 3.8 cm (1½ in.) I.D. hoses without difficulties. Pumping rates were adjusted to maintain line velocities in the 1.2 to 2.4 m per sec.(4 to 8 ft. per sec.) range to prevent settling. Lower velocities and high solids resulted in occasional line blockages. However, the lines were easily flushed out. In a routine operation where the lime sludge solids concentration could be controlled at 20 to 30%, line blockages should be almost entirely eliminated.

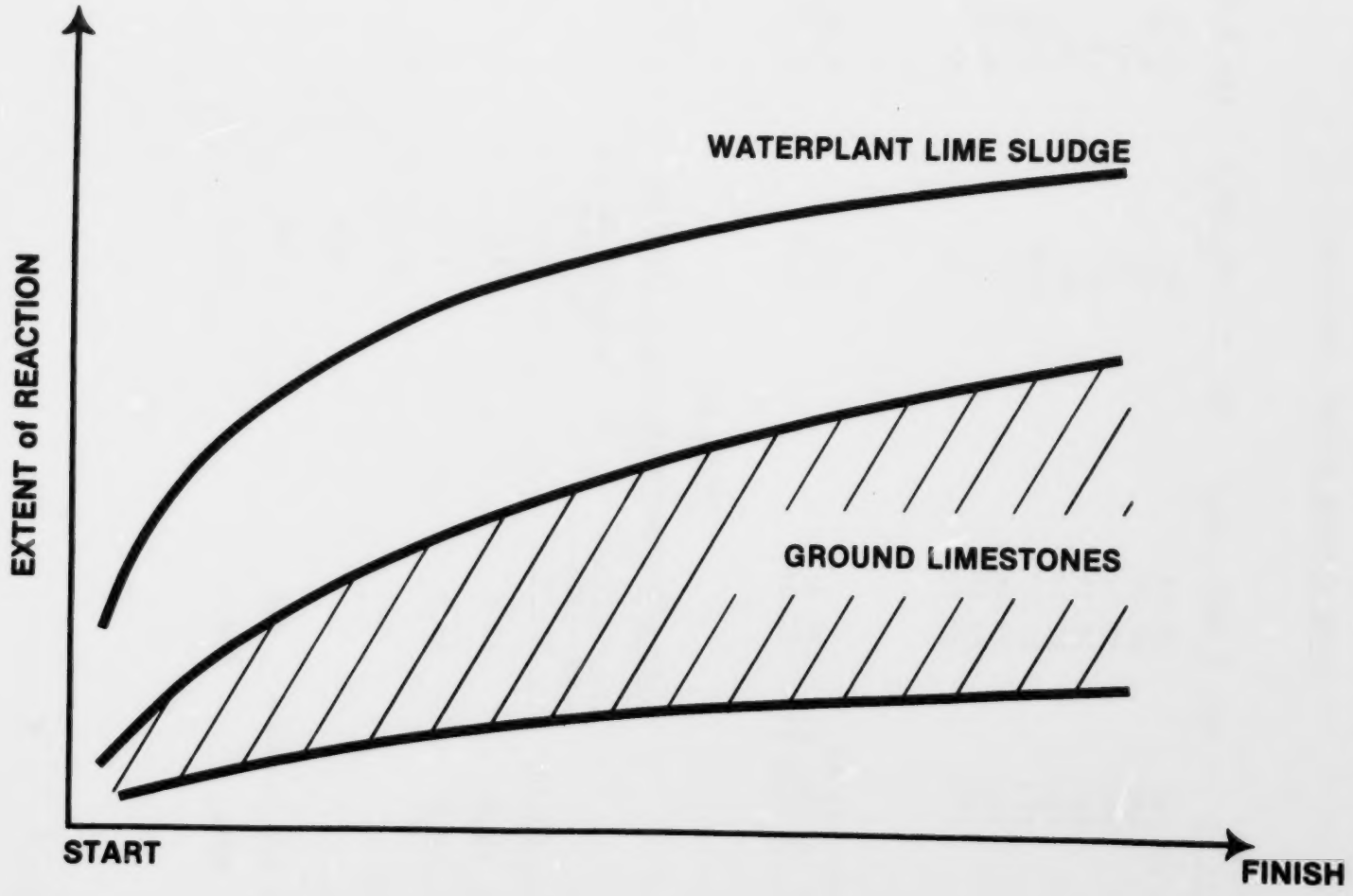

Figure 2-8: RELATIVE REACTIVITIES OF LIMESTONES AND LIME SLUDGE

TABLE 2.2

LIME SLUDGE SLURRY ANALYSIS

Date/Time Test	wt. % $CaSO_4 \cdot 2H_2O$	wt. % $CaSO_3 \cdot \frac{1}{2}H_2O$	wt. % $CaCO_3$
10/28/78 (A)	83.62	-0-	1.59
(B)	88.40	-0-	1.14
(C)	89.12	-0-	-0-
(D)	90.79	-0-	-0-
(E)	90.79	-0-	-0-
(F)	87.44	1.43	2.84
(G)	89.36	-0-	2.05
(H)	84.58	-0-	6.25
(I)	87.12	-0-	2.50
Average values tests (A thru D)	87.98	-0-	0.68
tests (E thru I)	87.86	0.28	2.73

TABLE 2.3

LIME AND LIMESTONE SLURRY ANALYSES

Slurry Solids	Lime Slurry May 1976 Wt. %	Limestone Slurry May 1977 Wt. %
$CaSO_4 \cdot 2H_2O$	33.4	77.5
$CaSO_3 \cdot \frac{1}{2}H_2O$	54.5	1.0
$CaCO_3$	3.7	17.3
$MgCO_3$	-	0.8
Acid Insoluables	4.6	3.4
TOTAL	96.2	100.0

TABLE 2.4

LIME SLUDGE SPECIFIC GRAVITY AND SOLIDS CONTENT

Date	Time	Specific Gravity	wt. %* Solids	Sample Location
10/23/78	15:40	-	(8.86)	Tank Truck
10/27/78	9:00	-	(23.32)	Thickener u' Flow
"	16:30	-	(12.82)	"
10/28/78	23:10	1.07	10.04	"
"	19:10	1.000	11.8	"
"	6:10	1.064	9.6	"
10/29/78	14:10	1.336	40.0	"
	10:00	1.12	17.0	"
"	2:10	1.072	10.7	"
"	22:10	1.29	35.7	"
10/30/78	2:10	1.26	32.8	"
"	6:10	1.26	32.8	"
"	12:00	1.047	7.1	"
"	16:00	1.31	37.6	"
10/31/78	8:10	1.21	(24) 27.6	"
"	11:40	1.32	38.6	"
"	20:00	1.262	33.0	"
"	15:40	1.085	12.5	"
11/1/78	0:10	1.276	34.4	"
"	4:00	1.31	37.6	"
"	8:00	1.3	36.7	"

* These values were calculated from the S.G. Data using a value of 2.7 for the S.G. of the solid phase and 1.0 for the water phase. The values in brackets are moisture balance measurements.

SECTION 3

SURVEY OF WATER PLANTS

SCOPE OF SURVEY

There are numerous sources of data regarding water supply and use in the United States. Two references which highlight major users were relied upon for this survey:

Public Water Supplies of 100 Largest Cities in the United States, 1962.
Geological Survey Water Supply paper No. 1912.

Operating Data For Water Utilities 1965 to 1970, American Water Works Association (AWWA) Statistical Report No. 20112.

These references were used to identify major water softening plants using lime-soda ash processes. In addition, a narrowing of the selection was based on the location of high sulfur coal deposits and a concentration of the industry.

Figure 3-1 illustrates hardness characteristics of water supplies and Figure 3-2 illustrates the location of coal resources. A comparison of these figures, points out a somewhat unique set of conditions existing in Ohio, Indiana and Illinois. These states have both large deposits of high sulfur coal and relatively high levels of hardness in their water supplies. In addition, these states are highly industrialized and are among those states with the highest SO_2 emissions. Other states were included in the survey to obtain data from areas which may be able to reuse lime sludge in the future and to get a good picture of the variability of lime sludge characteristics.

Sources of Lime Sludge

A survey of water treatment plants in the twenty one cities listed in Table 3.1 was made. The cities were selected because they have large water treatment systems and they were listed as users of lime for water softening in either of the two reference sources cited above.

Sixteen of the twenty one cities surveyed reported that they were currently using lime to soften water and four said they were not. One of the four, Saginaw, Michigan, stopped using lime after 1975 because of the cost. Two of the fifteen users of lime softening recalcine the lime sludge and reuse the lime. The rest dispose of a total of approximately 3.8×10^5 Mg per year (4.3×10^5 TPY) of lime sludge as solid calcium carbonate or an average of 2.7×10^4 Mg per year (3.0×10^4 TPY) for each city.

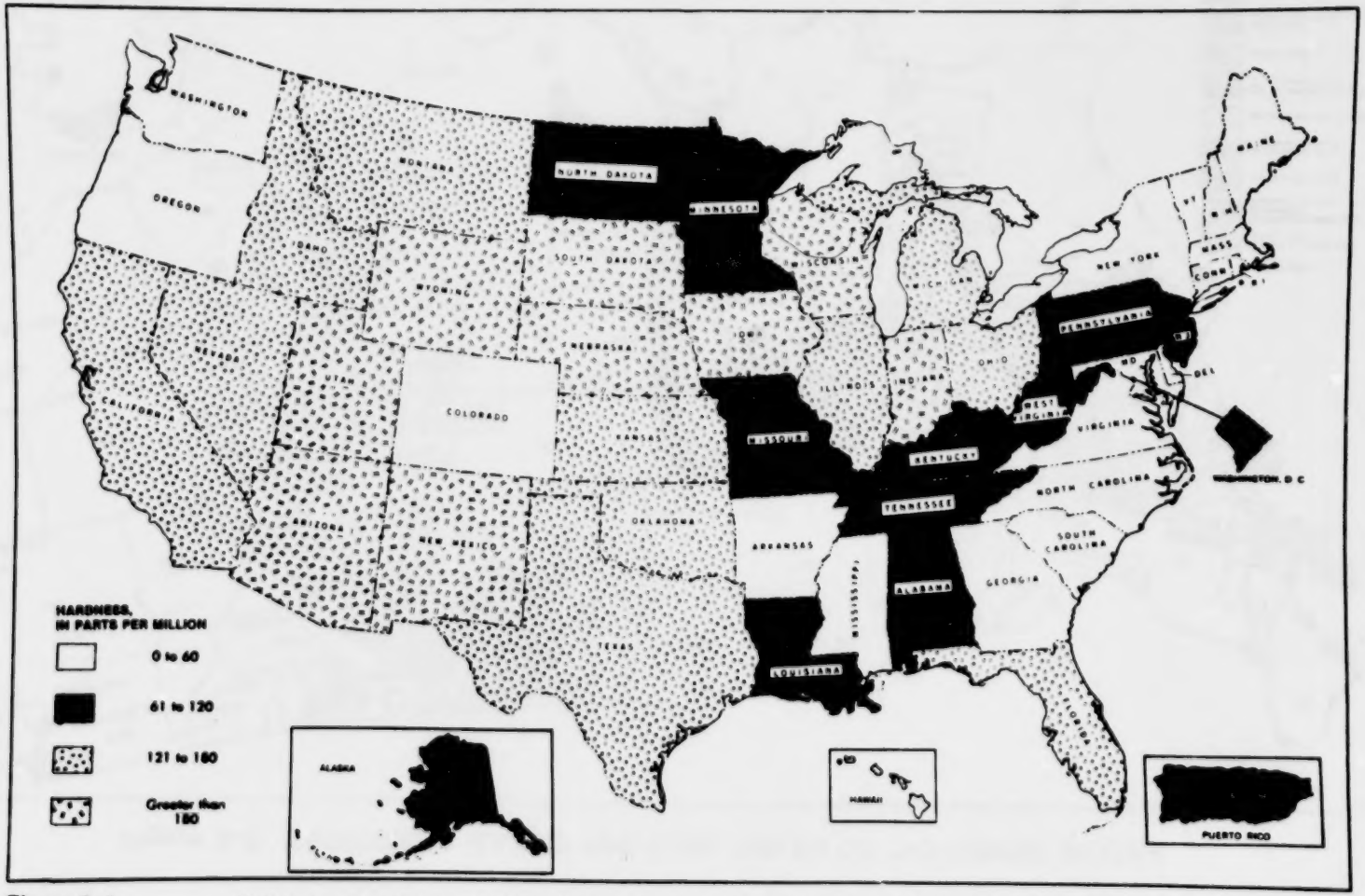

Figure 3-1 *Weighted average hardness, by States and Puerto Rico of water delivered from 1,596 public supplies, 1962.*

Figure 3-2: KEYSTONE'S MAP OF THE COAL FIELDS OF THE UNITED STATES

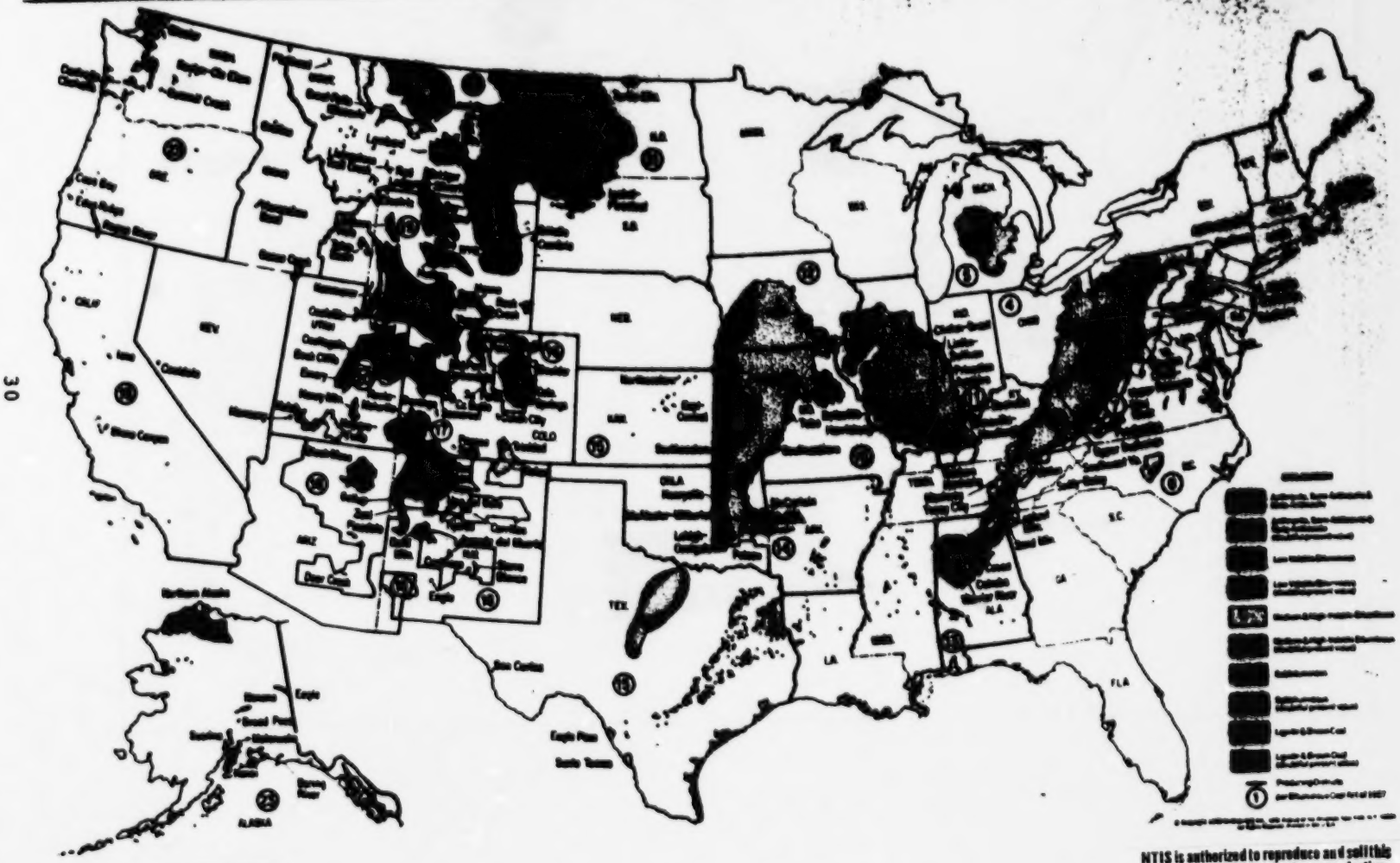

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TABLE 3.1

WATER PLANT SURVEY DATA SUMMARY

Town	State	Lime Softening	Hardness In (PPM)	Hardness Out (PPM)	Hardness Reduction (PPM)	Water Treated 10^7 l/day (Mil Gal/day)	Lime Consumption 10^3 Mg/year (Ton/yr)	Estimated Dry $CaCO_3$ Disposed 10^3 Mg/year (Ton/yr)	Final Sludge Disposal	Sludge On Hand
Quincy	Ill	Yes	180	112	68	2.6 - 3.0 (7-8)	1.03 (1139)	3.69 (4066)	River	None
Kankee	Ill	Yes	300	100	200	3.8 (10)	1.81 (2000)	6.44 (7100)	Quarry (Pond)	40 yrs worth
Pittsburg	Pa	No								Sanitary Landfill
Saginaw	Mich	Stopped in 1975								
Flint	Mich	No								
Westview	Pa	No								
Columbus	Ohio	Yes	170	100	70	30.3 (80)	8.28 (9125)	29.80 (32850)	Landfill	500 Acre Ft
Dayton	Ohio	Yes	350	150		32.2 (85)	-	None	All $CaCO_3$ is recalcined back to CaO	
Bloomington	Min	Yes	314	100	214	2.6 (7)	2.27 (2500)	8.10 (8925)	Landfill	No Estimate
Omaha	Neb	Yes	70 PPM Reduction		70	32.2 (85)	- -	9.25 (10200)	Lagoon	No Estimate
Oklahoma City	Okl	Yes	308	204	104	24.2 (64)	7.13 (7862)	25.49 (38100)	Pond	Removed Periodically
Austin	Texas	Yes	(Variable for 3 Plants)			24.6 (65)	9.15 (10083)	32.02 (35300)	Landfill Very	Large Amounts
Dallas	Texas	Yes	93	67	26	75.7 (200)	26.93 (29680)	96.16 (106200)	Lagoon	$6x10^6$ Ft
Ft. Wayne	Ind	Yes	279	86	193	12.5 (33)	9.98 (11000)	33.84 (37300)	Lagoon-Landfill	Removed Periodically to Landfill
Des Moines	Iowa	Yes	350	125	225	13.3 (35		38.0 (41900)	Lagooned Since 1949	12' Deep
Topeka	Kansas	Yes	181	67	114	8.3 (22)		6.89 (7600)	River	None
New Orleans	La	Yes	143	113	30	51.1 (135)		11.16 (12300)	River	None
St. Paul	Minn	Yes	175	80	95	20.8 (55)		None	Reclined & Reused	
Kansas City	Missouri	Yes	250	125	125	40.3 (106.5)		36.74 (40500)	River	None
St. Louis	Missouri	Yes	235	110	125	45.4 (120)		41.37 (45600)	River	None

TOTAL 3.8×10^8 Kg/Year (4.3×10^5 Ton/Yr)

AVERAGE (3.0×10^4 Ton/Yr)
(For 14 Cities) 2.7×10^7 Kg/Year

Lime-sludge is usually disposed of in one of 3 ways; river dumping, landfilling or lagoon/ponding. Of the fifteen cities which dispose of sludge, 5 river dump 1.08×10^5 Mg per year (119,000 TPY), 4 landfill 1.04×10^5 Mg per year (114,400 TPY) and 5 lagoon/pond 1.75×10^5 Mg per year (193,300 TPY). In the future, river dumping may be precluded due to environmental regulations.

In addition to the annual production of lime sludge, existing lagoons and landfills at many sites could be excavated to provide a substantial increase in the supply of lime sludge. Among the sites surveyed, Columbus, Ohio and Des Moines, Iowa each have approximately 8×10^5 Mg (9×10^5 T) of lime sludge in landfills or lagoons.

In addition to the cities surveyed, those listed in Table 3.2 were identified by the AWWA report No. 20112 as having water softening facilities.

A breakdown of total lime sludge tonnage by state is listed in Table 3.3. This table includes estimated tonnages determined by the survey and projected tonnages which were based on the total amounts of water (as listed in Table 3.2) softened in each state.

The information presented in Tables 3.1, 3.2 and 3.3 on water softening facilities, represent only a portion of the facilities presently practicing lime softening. Many facilities do not supply data to the AWWA, and the AWWA lists do not include captive industrial facilities.

In the states listed in Table 3.2, an average of 596×10^7 l per day ($1,574 \times 10^6$ gal per day) of water was softened out of a total water usage of $1,420 \times 10^7$ l per day ($3,749 \times 10^6$ gal. per day). This water was consumed by 25.8 million persons. The total population of these states in 1970 was 64.6 million persons whose total water consumption was approximately $3,554 \times 10^7$ l per day ($9,426 \times 10^6$ l per day)[4] if the same proportion of this water was softened, approximately $1,491 \times 10^7$ l per day) would have been treated. This amount of treatment would result in 1,816 Mg per year (2.0×10^6 TPY of lime sludge solids.

The population of the states listed in Table 3.2 and 3.3 is approximately 30% of the total U.S. population. Water supplied to the other 70% of the population is softened but to a lesser extent. This softening results in additional lime sludge generation.

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[4] Based on an average per capita consumption of 146 gal. per day.

TABLE 3.2

WATER PLANTS USING LIME SOFTENING
AND AVERAGE DAILY WATER RATES

ILLINOIS	MM gal/Day	10^7 l/Day
Bloomington	7.36	2.79
Champaign-No Ill. Wtr	12.53	4.74
Edwardsville	1.36	0.52
Jacksonville	3.29	1.25
Kankakee	10.02	3.79
La Grange	2.05	0.78
Moline	6.04	2.29
Peru	1.70	0.64
Quincy	7.71	2.92
Springfield	19.73	7.47
State Total	71.80	27.19
INDIANA		
Connersville	4.62	1.75
Fort Wayne	33.00	12.49
State Total	37.62	14.24
IOWA		
Ames	3.53	1.34
Cedar Rapids	17.46	6.61
Council Bluffs	7.53	2.85
Des Moines	34.34	13.00
DuBuque	6.77	2.56
Fort Madison	1.51	0.57
Marshalltown	3.81	1.44
Newton	2.81	1.06
Ottumwa	4.30	1.63
Spencer	0.94	0.36
West Des Moines	1.49	0.56
State Total	84.49	31.98

TABLE 3.2 Continued

	10^6 Gal/Day	10^7 l/Day
KANSAS		
Chanute	1.58	0.60
Coffeyville	3.92	1.48
Emporia	4.50	1.70
Independence	1.84	0.70
Junction City	2.11	0.80
Lawrence	6.33	2.40
Leavenworth	3.68	1.39
Manhattan	1.31	0.50
Mission-Johnson County	16.28	6.16
Ottawa	1.71	0.65
Pittsburg	2.69	1.02
Salina	6.11	2.31
Topeka	22.0	8.33
Witchita	38.06	14.41
State Total	112.12	42.44
LOUISIANA		
New Orleans	135.00	51.1
State Total	135.00	51.1
MICHIGAN		
Ann Arbor	17.40	6.59
Bay City	11.89	4.50
Iron Mountain	1.68	0.64
Lansing	21.92	8.30
Saginaw	28.02	10.61
Ypsilanti	9.11	3.45
State Total	90.02	34.07
MINNESOTA		
Bloomington	7.00	2.65
Fergus Falls	1.68	0.64
Moorhead	2.85	1.08
Richfield	3.68	1.39
Roseville	3.04	1.15
St. Paul	55.13	20.87
State Total	73.38	27.77

TABLE 3.2 Continued

MISSOURI	10^6 Gal/Day	10^7 l/Day
Gladstone	1.64	0.62
Kansas City	106.50	40.31
Marshall	1.81	0.69
St. Louis County	120.00	45.42
State Total	226.50	87.04
NEBRASKA		
Bellevue	1.60	0.61
Omaha	85.00	32.17
State Total	86.60	32.78
OHIO		
Columbus	80.00	30.28
Alliance	5.91	2.24
Ashland	2.78	1.05
Chillicothe	2.47	0.93
Coshocton	5.19	1.96
Cuyahoga Falls	6.28	2.38
Dayton	70.41	26.65
Defiance	3.80	1.44
Delaware	2.06	0.78
Marietta	3.91	1.48
Massilon-Ohio Wtr Serv	4.41	1.67
New Philadelphia	1.85	0.70
Piqua	3.98	1.51
Reynoldsburg	1.13	0.43
Shelby	1.32	0.50
Sidney	2.64	1.00
Struthers-Ohio Water Serv	3.55	1.34
Troy	2.47	0.93
State Total	204.16	77.27
OKLAHOMA		
Oklahoma City	64.00	24.22
Norman	3.65	1.38
State total	67.65	25.60

TABLE 3.2 Continued

TEXAS	10^6 Gal/Day	10^7 l/Day
Austin	50.40	19.08
Corpus Christi	73.86	27.96
Dallas	181.68	68.77
El Paso	62.79	23.77
Greenville	3.32	1.26
Mc Allen	6.99	2.65
Temple	5.41	2.05
State Total	384.45	145.51
TOTAL FOR ALL STATES	1,573.79	595.66

TABLE 3.3

LIME SLUDGE TOTALS BY STATE

State	Estimated Lime Sludge Mg/Yr (Tons/Yr	Projected Lime Sludge Mg/Yr (Tons/Yr
Illinois	10,130 (11,166)	41,020 (45,220)
Indiana	33,840 (37,300)	38,590 (42,510)
Iowa	38,010 (41,900)	93,520 (103,090)
Kansas	6,900 (7,600)	35,140 (38,732)
Louisiana	11,160 (12,300)	11,160 (12,300)
Michigan	-	17,550 (19,354)
Minnesota	8,100 (8,925)	84,880 (93,560)
Missouri	78,110 (86,100)	78,990 (87,070)
Nebraska	9,250 (10,200)	9,450 (10,392)
Ohio	29,800 (32,850)	76,050 (83,833)
	379,460 (4.3×10^5	725,530 (8.0×10^5

Data published in the Lime Chapter of the Bureau of Mines 1977 Minerals Year Book indicates that 1.5 x 10^6 Mg (1,652,000 T) of lime (CaO) is used for water purification. Most of this lime is used for softening of domestic and industrial water supplies. A conservative estimate of total annual lime sludge production based on this lime consumption figure is 3.6 to 4.5 x 10^6 Mg (4 to 5 million dry tons) per year.

This estimate is in basic agreement with that extraplated from the data in the AWWA publication as summarized in Tables 3.2 and 3.3.

Characteristics of Lime Sludge

Lime sludges were obtained from the ten municipal lime water softening systems listed in Table 3.4. In addition samples from the water treatment plant at Rickenbacker AFB were analyzed. Results of the chemical and particle size analyses for these ten samples are also listed.

It can be seen from the data in Table 3.4 that, with a few exceptions (i.e. St. Louis and New Orleans), the chemical and physical characteristics of lime sludges are very similar. Total alkalinity for the eight samples exclusive of St. Louis and New Orleans, ranged from 74.3 to 96.8% with an average of 89.49% and an average hydroxide content of 1.6%. Acid insolubles ranged from 0.13 to 16.0% with an average of 3.87%. The mass median particle diameter for the samples exclusive of St. Louis, New Orleans and Topeka ranged from 2.8 to 10.3 microns with an average of 6.71 microns[5].

The lime sludge used for the testing at RAFB was obtained from the Morse Road water plant in Columbus. The Morse Road samples number 20 and 21 in Table 3.4, had an average $CaCO_3$ alkalinity of 88.34% and hydroxide content of 3.3%, acid insolubles of 4.29% and a particle size of 6.7 microns.

Summary

Based on the estimated annual lime sludge production of 1,816 mg per year (2.0 x 10^6TPY), its proximity to present or potential consumers of high sulfur coal in the midwest and its relative uniformity regarding both chemical composition and physical characteristics, this material has the potential to supplant or supplement other reagents at many FGD installations.

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[5] See Table 3.4

TABLE 3.4

LIME SLUDGE SURVEY SAMPLE ANALYSES

Sample No.	City	Wt. % $CaSO_4 \cdot 2H_2O$	Wt. % $Ca(OH)_2$ & $Mg(OH)_2$	Wt. % $CaCO_3$	Wt. % Acid Insoluables	Alkalinity as $CaCO_3$	Wt. % Ca	Wt. % Mg	Wt. % $SO_4^=$	Wt. % Cl-	Wt. % Solids	Mass Median Particle Size Microns
12	St. Paul	4.78	0.00	81.87	0.13	91.31	33.24	2.25	0.46	0.14	10.2	9.2
13	Ft. Wayne	1.19	0.00	76.42	4.64	74.30	38.89	2.34	0.52	0.11	Dry	2.8
14	RAFB	2.39	0.00	78.45	0.36	96.06	25.55	2.29	0.87	0.08	3.2	7.9
15	RAFB	0.00	0.00	80.51	0.22	92.23	28.77	2.02	3.34	0.28	39.5	9.8
16	Kansas City	0.00	8.71	56.40	6.97	90.30	27.00	8.29	1.49	0.22	4.2	10.3
17	Bloomington Minn.	0.00	0.00	82.56	0.23	95.54	40.95	2.33	0.16	0.23	47.5	6.0
											47.1	18.0
18	St. Louis	4.78	0.00	23.88	61.26	24.33	11.33	0.73	0.37	0.27	0.10	*
19	New Orleans	4.78	1.87	61.29	21.14	67.16	25.39	1.99	1.75	0.28	8.8	6.8
20	Columbus	2.39	3.11	83.47	2.07	92.32	26.47	1.71	0.20	0.28	70.6	6.5
21	Columbus	5.02	3.58	73.91	6.51	84.36	23.81	2.74	1.01	0.23	6.7	6.0
22	Des Moines	4.30	4.36	74.82	2.16	94.28	31.82	3.97	0.67	0.17	0.10	*
23	Topeka	1.43	0.78	82.44	5.64	86.55	63.17	1.95	2.75	0.17		
37	Dallas	0.00	0.00	76.53	16.08	79.80	29.20	0.32	1.29	0.07	53.2	3.6
38	Dallas	0.00	0.00	86.65	1.41	96.81	32.77	1.57	1.54	0.08	40.5	4.95

* These samples were too dilute to obtain sufficient solids for particle size determinations.

SECTION 4

PROPOSED LIME SLUDGE HANDLING SYSTEM

The handling of lime sludge is a familiar operation at many water plants, and periodic lagoon emptying is practiced at many sites.

The lime sludge samples obtained in the water plant survey and other data[6] indicate that lime sludges can be dewatered with proper lagoon operation to 50% solids. This material can be handled with conventional earth moving equipment and transported by truck.

The specifications listed in Table 4.1 define design criteria for a proposed lime sludge handling system. This system is suitable for the R-C Bahco System at RAFB or for any other 2 to 4% sulfur coal fired boiler with a gross heat input of 2.1×10^8 kj per hour (200 mm BTU per hour).

LIME SLUDGE HANDLING SYSTEM DESCRIPTION

The lime sludge handling system at the water treatment plant disposal site will require only a front-end loader and a gasketed dump truck, similar to those currently in use[6], to transport dewatered lime sludge. The front-end loader will scoop the dewatered lime sludge at 50% solids concentration from the lagoon and deposit in into the dump truck for transport to the boiler location. Careful lagoon management is essential to achieve a 50% solids concentration. The lagoon supernate or accumulations from heavy rainfall must be decanted from the lagoon prior to each fresh sludge application and at no time should ponding of the supernate be allowed. This is necessary because submerged lime sludge will dewater to only about 30% solids. Providing lagoon under drains is recommended as the most reliable method to reduce the water content to consistently produce a 50% solids sludge.

The lime sludge handling system at the boiler site, illustrated schematically in Figure 4-1, will consist of a sludge storage area, a front-end loader, two mixing and storage tanks each equipped with a feed hopper and screw conveyor, and two independently operated slurry feed pumps. Plan and elevation views of this equipment are shown in Figures 4-2 and 4-3. This system utilizes below ground concrete storage and mixing tanks.

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[6] Journal AWWA October 1975
From Lagooning to Farm Land Application G. Russel, Pg. 585 and AWWA Research Foundation August 1969, Page 54, Program Number 12120ERC

TABLE 4.1

LIME SLUDGE HANDLING SYSTEM DESIGN CRITERIA

I. Water Plant Disposal Site Specifications:

1. Average rate of lime sludge removal 13.6 Mg per day (15 tons per day) dry solids as calcium carbonate.

2. Type of lime sludge disposal site: Lagoon without substantial surface evaporation.

3. Dump truck transport.

4. Weekly removal.

5. Loading equipment
Front end loader or equivalent to be supplied by water plant operator.

6. All equipment to be designed for outdoor operation in midwest climate.

II. Lime Sludge User Site Specifications:

1. Average rate of lime sludge use:

13.6 Mg per day (15 tons per day) dry solids diluted to 25% solids for use in the SO_2 scrubbing system.

2. Type of lime sludge storage: 95.3 Mg (105 ton) (at 100% solids) one week supply dump pile with suitable mixing and dilution equipment to prepare 25% solids.

NOTE: Front end loader or equivalent to be supplied by scrubbing system owner.

3. Unloading equipment:

Dump truck unloading to be accomplished without assistance of plant operating personnel.

4. All equipment to be designed for outdoor operation in midwestern climate.

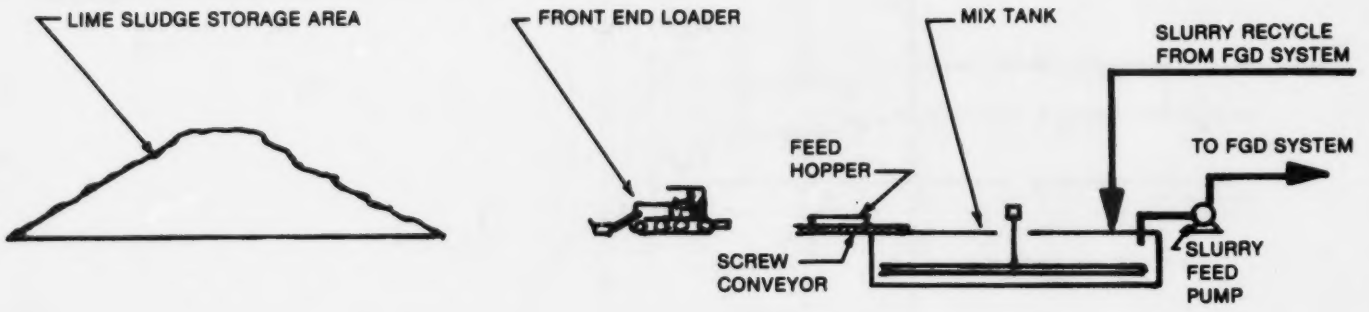

Figure 4-1: LIME - SLUDGE HANDLING SYSTEM

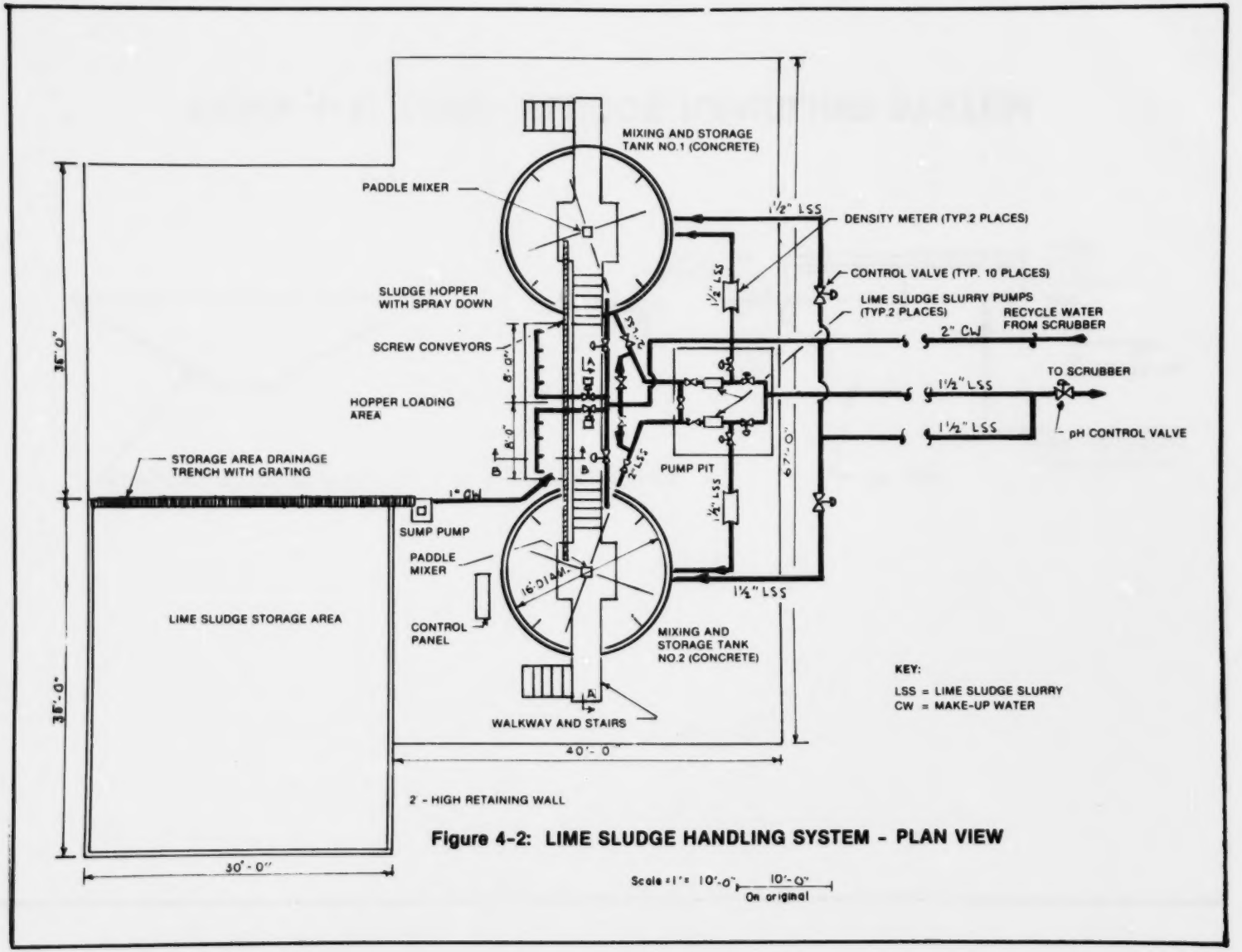

Figure 4-2: LIME SLUDGE HANDLING SYSTEM - PLAN VIEW

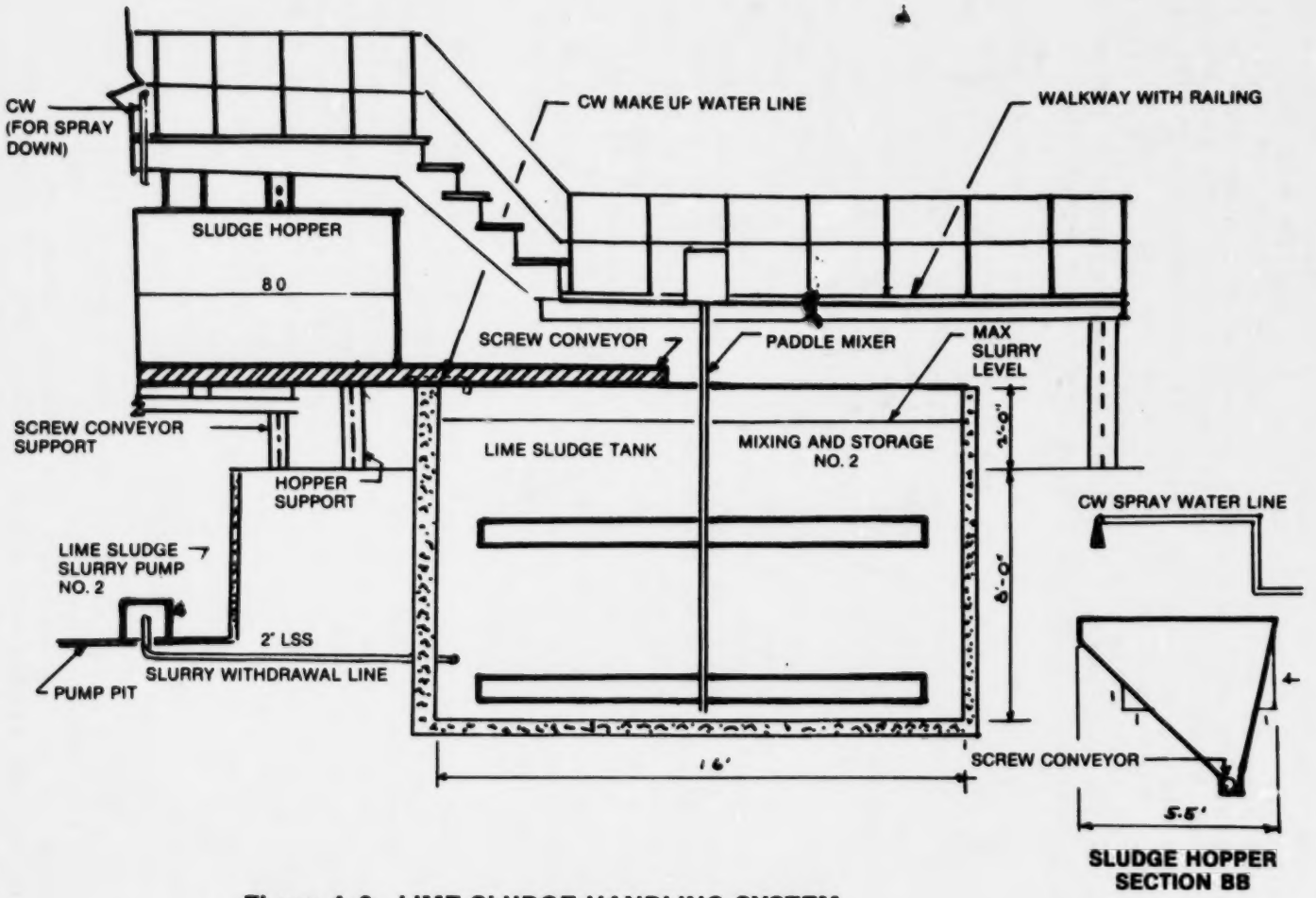

Figure 4-3: LIME SLUDGE HANDLING SYSTEM

SECTION. AA
SCALE: ¼" = 1'-0"

4"
ON ORIGINAL

The system is designed to receive 50% lime sludge, reslurry it to a 25% solids concentration, and feed it to the FGD system. A lime sludge storage area is provided to hold one week's supply of 50% sludge at a utilization rate of approximately 13.5 Mg (15 tons) of dry solids per day. The storage area is surrounded on three sides by a 0.6 m (2 ft.) high retaining wall and has a trench with a sump pump on the open side to collect any water which drains from the sludge. The two mixing and storage tanks are provided with paddle type mixers. Each tank is sized to hold one day's supply of 25% solids so that while one tank is reslurrying the other will be feeding the scrubber. Two air operated diaphragm pumps are also provided to pump the 25% slurry to the scrubber.

The system is designed to be controlled from both a local control panel by the front-end loader operator and from the FGD system control panel. During normal operation, both paddle mixers and feed pumps will operate continuously. In the tank which is being used to feed the scrubber, the pump discharge control valves will be set to deliver the full 130 l per min. (35 gpm) pump output to the scrubber area. An automatic pH control valve at the scrubber will allow approximately 25 l per min (7 gpm) to be fed to the scrubber system while the remaining 105 l min per (28 gpm) will be recycled back to the feed tank. This procedure maintains a 1.2 to 2.4 m per sec. (4 to 8fps) velocity in the 3.8 cm (1½ in.) feed and recycle lines. A level probe in the feed tank will signal the FGD system operator when the slurry level is at a low level. At this time the operator should energize the pump discharge control valves so that the pump for the second storage tank feeds the scrubber system and the first pump is in the full recycle mode and is returning the full 130 l per min. (35 gpm) into the mixing tank. A new batch of sludge should now be prepared in the first mix tank.

When preparing a fresh batch of slurry, the front-end loader operator first turns on the appropriate screw conveyor and opens the automatic control valve in the make up water line. This valve will automatically close when it receives a signal from the tank level probe indicating that approximately 80% of the water required to prepare one batch has been added to the tank. The front-end loader operator then dumps a predetermined number of buckets of the 50% sludge from the storage area into the appropriate tank hopper. This sludge is fed into the tank center at a constant rate by the screw conveyor. Finally the front-end loader operator opens the automatic valve on the make-up water line which washes the sludge remaining in the hopper into the tank. This valve will automatically close when it receives a signal from the density meter located in the pump recycle line indicating that the sludge is at the desired 25% solids concentration. If excessive 50% sludge was added so that the 25% concentration is not achieved, a high level signal from the level probe also closes this valve to prevent the tank from overflowing.

In the event that the FGD scrubber system is not operating for a period of time, a flushing system is provided to wash the slurry out of the pipes and pumps. By manipulating the manual valves on the pump suction, the solids can be flushed either back into the mix tanks or through the pumps to the scrubber system.

An equipment list and preliminary capital cost estimate are presented in Table 4.2 for the equipment described above. The total capital cost for this system, which includes below ground concrete tanks, was estimated to be approximately $100,000.

The system as proposed provides 100% redundancy for all major equipment items. If an existing reagent system could be put on standby operation when a lime sludge system is added to the facility the redundancy could be eliminated. This would result in a cost saving of approximately 40% for the lime sludge system.

TABLE 4.2

LIME SLUDGE HANDLING SYSTEM COST SUMMARY

Sludge Feed System at Boiler -
Equipment and Materials List and Construction Cost Estimate

Equipment and Materials	Installed Cost Estimate
Mechanical Process Equipment	
2 - KW (20 Hp) Paddle Type Mixers	$20,000
2 - 0.15 M (6") x 4.6 M (15') Screw Conveyors	8,000
2 - 130 l/min (35 gpm) Air Operated Diaphragm Pumps	4,000
1 - 60 l/min (15 gpm) Sump Pump	1,500
2- 4.9 m (16') diam x 3 m (10') high inground concrete tanks	8,500
2 - 2.4 m (8') x 1.7 m (5½') x 1.5 m (5') steel sludge hoppers	3,000
Sub Total	$45,000
Other Materials Including	$34,370
Piping Instumentation Sludge Storage Access & Supports	
Sub Total	$79,370
Contingency (25%)	$19,850
APPROXIMATE TOTAL COST	$99,220

SECTION 5

ECONOMICS OF LIME SLUDGE UTILIZATION

One of the most important objectives of this program was to determine the economic viability of using lime sludge as an alternate FGD scrubbing reagent. This section presents both the economics of lime sludge utilization and a comparison of these costs with those for lime and limestone.

For this economic evaluation an industrial coal fired boiler with an FGD system having a 180,000 lb per hour steam generating capacity will be used. A plant operating rate of 75% was selected and a typical midwestern coal with a 2.33 x 10^4 kJ per Kg (10,000 BTU per lb) heating value and 3% sulfur was selected as the fuel. Approximately 5.4 x 10^4 Mg (60,000 tons) of coal would be burned annually. An SO_2 removal efficiency of 80% is required to limit SO_2 emissions to less than 0.516 mg per kJ (1.2 lbs per mm BTU) of coal fired.

Based on the above requirements, the reagent consumptions listed in Table 5.1 are necessary.

LIME SLUDGE SYSTEM OPERATING COSTS

The operating costs for a lime sludge handling system include utilities, operating and maintenance labor and overhead, depreciation, taxes, insurance and the cost of obtaining the lime sludge.

For this analysis the following assumptions have been made:

1. The lime sludge is available within a fifteen mile radius of the FGD system.

2. Lime sludge will be transported in gasketed dump trucks owned and operated by a local trucking contractor.

3. One eight-hour day of hauling per week will be needed to transport lime sludge from a local water treatment plant to the FGD system using two trucks.

4. The water treatment plant will load lime sludge into the trucks at no charge for the sludge or for loading.

5. The truck operator will unload at the FGD site without assistance from plant operating personnel.

TABLE 5.1

REAGENT REQUIREMENTS AND COSTS

	10^3 Mg/Year (Tons Per Year)	Purity	Reagent-SO_2 Stoichiometry [6]
Lime	2.54 (2800)	90%	0.8
Limestone 90%-74 microns (-200 mesh)	5.37 (5920)	95%	1.0
Lime sludge	4.70 (5180)	90%	0.84

	Estimated Delivered Cost Per Ton	Annual Cost
Lime	$42.00	$117,600
Limestone	$13,00	& 77,000

TABLE 5.2

INCREMENTAL OPERATING COST FOR LIME SLUDGE UTILIZATION SYSTEM

Capital Cost	$100,000
Power 128,000 KWH @ $0.25/KWH	$ 3,200
Water no additional cost	--
Operating labor 800 manhours @ $8.00 per hr.	6,400
Supervision 200 manhours @ $10.00 per hr.	2,000
Maintenance labor & materials 3% of capital cost	3,000
General overhead 75% of operating labor	6,300
Depreciation 10 year straight line	10,000
Texas & insurance 2% of capital cost	2,000
Lime sludge transportation	22,000
TOTAL ANNUAL COST	$54,900

Total lime sludge 4.7 x 10^3 Mg (5180 tons) per year dry

Total cost per Mg of lime sludge $11.68 ($10.60 per ton)

Total coal consumption 5.44 x 10^4 Mg (60,000 tons) per year

Total cost per Mg of coal burned $1.01 ($0.92 per ton)

[6] Based on available alkalinity

Based on the above assumptions which allow an hour and a half for handling each load of lime sludge and current trucking costs obtained from a trucking contractor in Ohio, lime sludge transportation will cost $22,000 per year. This is based on a cost of $220 per day per truck and fifty days of hauling per year.

The anticipated operating costs for lime sludge utilization is summarized in Table 5.2. The annual cost savings for lime sludge when compared to those for lime and limestone as listed in Table 5.1 above, is $62,700 per year when compared to lime and $22,100 when compared to limestone.

It is important to note that in this analysis no value is given to the lime sludge. In actual practice lime sludge has a substantial negative value to most water plant operators because of disposals costs.

Based on earlier estimates[7] the cost of lagoon disposal of lime sludges was $5.50 to $18.60 per Mg ($5 to $16 per ton) of dry solids in 1969. Current disposal costs are estimated to be $11 to $22 per Mg ($10 to $20 per ton) based primarily on increased labor and sludge lime removal costs.

The cost savings cited above represent the minimum reductions available since the negative value of the sludge has not been considered. Given these conditions in a captive situation such as the one at RAFB, where they have both a water treatment plant producing lime sludge and a FGD system, full credit for lime sludge disposal should be considered.

If an $11 per Mg ($10 per ton) credit was applied to the case described above the annual cost would be decreased by over $50,000. This would result in actual savings of approximately $113,000 when compared to lime and $72,000 when compared to limestone.

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[7] Disposal of water from water treatment plants AWWA Research Foundation Program No. 12120 ERC, August, 1969, Appendix Cost Analyses.

SECTION 6

CONCLUSIONS

Based on the results obtained in this test program for inlet SO_2 concentrations in the range of 300 to 500 ppm, the following conclusions can be drawn:

Lime sludge, when used as an FGD reagent, exhibits the following properties:

1. SO_2 removal capabilities and utilization are similar to lime up to a stoichiometric ratio of approximately 0.8.

2. Above a 0.8 stoichiometric ratio SO_2 removal capabilities and utilization begin to decrease toward values typical of limestone.

3. The composition of the reaction products when using lime sludges are similar to those obtained with limestone, that is, they are high in gypsum ($CaSO_4.2H_20$) content.

Based on present handling practices, lime sludges can be preapred for transport to FGD system use points by careful management of existing lime sludge lagoons and by using conventional dump trucks with minor modifications to minimize water leakage.

Lime sludge is available at many water treatment facilities in the midwestern states as well as in other locations in the United States.

Projected survey results indicate that 18.16×10^5 Mg (2,000,000 tons) per year of lime sludge may be available in Midwestern and Central States. The Bureau of Mines data on lime consumption, supports this conclusion.

Lime sludges from different geographical areas are similar in composition, alkalinity and particle size.

Lime Sludge can be pumped with conventional slurry pumps at solids concentrations in excess of 30% by wt. and alternate transportation by tank truck at 30% solids is feasible.

A lime sludge handling system for a typical industrial sized FGD installation is approximately $100,000.

Annual costs for lime sludge for a typical Industrial FGD system are $55,000 without credits for lime sludge disposal costs.

Lime sludge costs for a typical Industrial FGD System are $62,700 less than lime costs and $22,100 less than limestone. Lime sludge disposal credits would result in additional savings of approximately $50,000 per year.

SECTION 7

RECOMMENDATIONS

The results of this lime sludge utilization test program are very encouraging. Two significant problems associated with the protection and preservation of our environment are addressed; the disposal of water plant wastes and the costs of operating an FGD system. The integrated solution to these problems suggested by this study; the reuse of a waste product (lime sludge), is one of the most desirable ways to address our environmental problems.

Several additional steps are recommended in order to fully implement lime sludge utilization. These include:

A long term test at RAFB or some other facility to determine the long term effects of using lime sludge in an FGD system.

An expanded survey of lime sludge sources to include captive industrial and utility water treatment facilities.

An evaluation of the use of lime sludge as a supplemental reagent in existing utility FGD systems.

Testing of lime sludge as an FGD reagent at SO_2 concentrations in the 1000-2000 ppm range to define SO_2 removal capabilities, reagent utilization and FGD sludge characteristics.

APPENDIX A

CONVERSION FACTORS: BRITISH TO SI UNITS

To Convert Form	To	Multiply by
LENGTH		
Inch (in)	meter (m)	2.540×10^{-2}
foot (ft)	meter (m)	0.3048
miles (mi)	kilometer (km)	
AREA		
$inch^2$ (in^2)	$meter^2$ (m^2)	6.45×10^{4}
$foot^2$ (ft^2)	$meter^2$ (m^2)	9.290×10^{-2}
VOLUME		
$inch^3$ (in^3)	$meter^3$ (m^3)	1.639×10^{-5}
$foot^3$ (ft^3)	$meter^3$ (m^3)	2.832×10^{-2}
$foot^3$ (ft^3)	liter (l)	28.32
gallon (gal)	$meter^3$ (m^3)	3.785×10^{-3}
gallon (gal)	litre (l)	3.785
MASS		
ounce (oz)	kilogram (kg)	2.835×10^{-2}
pound (lb)	gram (g)	453.6
pound (lb)	kilogram (kg)	0.4536
grain (gr)	gram (g)	6.480×10^{-2}
Ton (T)	megagram (Mg)	0.9072
PRESSURE		
Inches W.C.$_2$ (in w.c.)	kilopascal (kPa)	0.2488
pounds/$inch^2$ (psi)	kilopascal (kPa)	6.895
TEMPERATURE		
degree Fahrenheit (^oF)	degree centrigrade (^oC)	$tc = \frac{5}{9}(t_f - 32)$
degree Rankin (^oR)	degree Kelvin (^oK)	0.5555
ENERGY		
British Thermal Unit (Btu)	joule (J)	1055.
British Thermal Unit (Btu)	kilojoule (kj)	1.055

POWER		
British Thermal Unit/hour (Btu/hr)	watt (w)	0.2931
British Thermal Unit/hour (Btu/hr)	kilowatt (kw)	2.931×10^{-4}
British Thermal Unit/horsepower (hp)	kilowatt (kw)	0.7457
DENSITY		
pound/foot^3 (lb/ft^3)	kilogram/meter^3 (kg/m^3)	16.02
pounds/gallon (lb/gal)	kilogram/meter^3 (kg/m^3)	119.8
VISCOSITY		
pound foot second/foot^2 (lb. ft/sec ft^2)	pascal-second (Pas)	47.89
MISCELLANEOUS		
cubic feet/minute (CFM)	meter^3/hour (m^3/hr)	1.699
gallons/1000 ft^3 (gal/M)	liter/meter^3 (l/m^3)	0.1337
gallon/minute (gal/min)	litre/minute (l/min)	3.785
grains/standard cubc foot (gr/SCF)	grams/normal meter^3 (g/nm^3)	2.288
feet/second (ft/sec)	meter/second (m/sec)	0.3048
pounds/1,000,000 Btu (lb/MM Btu)	milligrams/ kilojoule (mg/kJ)	0.4299
British Thermal Units/pound (Btu/lb)	kilojoule/kilogram (kJ/kg)	2.326

APPENDIX B

ANALYTICAL AND TESTING METHODS

B-1 Thermogravimetric Analysis

B-2 Analytical Procedure for SO_2 Wet Tests

B-3 Analytical Methods

APPENDIX B-1

THERMOGRAVIMETRIC ANALYSIS OF SOLIDS FROM BAHCO SCRUBBING PROCESS

General Procedure:

All analyses performed on lime-based scrubbing solids from the Bahco SO_2 Gas Removal Process at Rickenbacker Air Force Base utilized the specific technique of thermogravimetric analysis (TGA). This technique involved heating a prepared sample of solid phase material at a specific rate over a pre-determined temperature range and observing the weight change which results from solid state reaction occurring at some characteristic temperature.

After in-laboratory treatment, which includes drying at 30°C for 24 hours, breaking up the dried solids and riffling as many times as needed to obtain a representative sample of about 2.5 gms.; the prepared solid phase sample is then subjected to analysis on the thermobalance over a pre-programmed temperature range, (ambient to 980°C) at a specific heating rate (80°C per minute). The resulting thermogram will exhibit, in a general case, associated weight losses of waters of hydration from $CaSO_4.2H_2O$(130-200°C), ½ water of hydration from $CaSO_3.\frac{1}{2}H_2O$(400-450°C), dehydration of $Ca(OH)_2$ (575-625°C), loss on ignition from combustibles (700-750°C) and finally evolution of CA_2 from $CaCO_3$ (800-900°C). Measuring these losses and back calculating each for the particular constituent results in a total analysis of the solids, with the exception of any inert material, which would require separate testing.

In addition to the various calcium compounds which were determined by TGA, it also became necessary to determine the concentration of $MgCO_3$ present in the solid phase during the limestone phase of the test program. Since the limestone used in this phase of the study was dolomitic, the presence of $MgCO_3$ was noticed during initial thermogravimetric testing. To effectively separate the weight losses of CO_2 from $MgCO_3$, and the weight loss from the ignition of combustibles, which overlap at 650°C, it was necessary to reanalyze these samples in a nitrogen environment where combustion would not take place. The resulting weight loss in percent was then back calculated in the same manner as previously stated.

To insure the data obtained from TGA analyses produced a high degree of accuracy, an alternate wet chemical method was employed as a check. This wet test procedure uses the same prepared sample which is reacted in an absorption train assembly using hydrochloric acid to digest the sample.

As the sample digests in the acid medium, CO_2 and SO_2 are evolved and forced through the train by a stream of nitrogen gas. The evolved CO_2 and SO_2 gases are passed through a gas washing bottle filled with a 30% hydrogen peroxide solution, which traps any SO_2 forming H_2SO_4. The SO_2 free gas stream then passes through several moisture traps (P_2O_5 and anhydrous magnesium perchlorate) to a preweighed Miller bulb containing 20 mesh Ascarite, to absorb the CO_2.

After the digestion has been completed, the reaction flask solution is tested for insolubles, calcium content by EDTA titration (also magnesium content if applicable) and total sulfate by gravimetric means. The solution in the peroxide trap is titrated for SO_2 using a $BaCl_2$ titrant and Thorin as an indicator. The Miller bulb is weighed to determine the weight of CO_2 absorption. From data obtained from these tests we are able to perform a complete analysis of all the constituents previously mentioned. Data obtained by this procedure match TGA results within $\pm$ 5 percent in all samples tested.

In addition to the use of wet chemical methods to verify TGA data, the use of laboratory prepared samples using reagent grade chemicals similar to those to be determined were also tested by thermal means. Various ratios of $CaSO_4.2H_2O$ to $CaSO_3.\frac{1}{2}H_2O$ with amounts of $CaCO_3$ and $MgCO_3$ were analyzed by TGA. The data obtained from these TGA analyses also yielded results which were within $\pm$ 3 percent of the calculated percentages in the sample formulations.

Use of a thermogravimetric balance for lime or limestone based solids analysis is a rapid, reliable method for the determination of $CaSO_4.2H_2O$, $CaSO_3.\frac{1}{2}H_2O$, $Ca(OH)_2$, $MgCO_3$ and $CaCO_3$. The use of this instrument with occasional wet chemical methods produces data which is within $\pm$ 3 percent of other accepted analytical methods and in substantially less time than comparable wet chemical analyses.

APPENDIX B-2

ANALYTICAL PROCEDURE FOR SO_2 WET TESTS

This method for determining the SO_2 content of gas streams is only approximate and should be used only as a semi-quantitave check on SO_2 concentrations.

No temperature or pressure corrections have been incorporated, and the method should not be used below 100 ppm.

Apparatus:

1) 250 ml impinger with an open glass dip tube.
2) A dry test meter
3) A source of vacuum
4) 25 ml pipette
5) Vacuum tubing
6) Hose clamp

Reagents:

1) 3% Hydrogen Peroxide
2) 0.1N NaOH or 0.01 N NaOH
3) Methyl/Orange-Sylene Cyanol indicator

Procedure:

Inlet Samples (i.e., 500 + ppm SO_2) pipette 25 ml of 0.1 N NaOH into the 250 ml impinger, add 50 ml of 3% hydrogen peroxide. Add approximately 25 ml of deionized water. Add several drops of Methyl/Orange-Xylene Cyanol indicator.

Draw the gas sample through the impinger at 0.1 to 0.2 ft./min. Record the gas meter reading when the indicator turns from green to purple.

Outlet Samples (100 to 600 ppm SO_2) substitute 0.01 normal NaOH from 0.1 normal NaOH in the above procedure. Follow the same procedure as above.

The folloiwng equation can be used to calculate the SO_2 concentration:

$$SO_2 \text{ ppm} = \frac{10{,}000 \times (\text{NaOH Normality})}{\text{Meter Volume ft.}^3}$$

Note: Add the indicator within 15 minutes of running the test. If the indicator is added at an earlier time, it may be destroyed by the hydrogen peroxide in the impinger.

APPENDIX B-3

ANALYTICAL METHODS

Listed below are various physical and analytical methods which were employed in testing samples from the BAHCO GAS Cleaning Project at Rickenbacker Air Force Base:

Particle Size (Sub-Sieve) - BAHCO micro-particle classifier as per ASTM procedures

Particle Size (Sieve) - U.S. Standard Sieves as per ASTM procedures

Specific Gravity Determination - Use of calibrated cement pycrometer and ASTM procedure

Bulk Density - Use of ASTM procedure for compacted bulk density

Thermo-Gravimetric Analysis - Used in analyzing solids from scrubbing process; limestone and lime samples for $CaSO_4.2H_2O$, $CaSO_3.\frac{1}{2}H_2O$ and $Mg(OH)_2$, $MgCO_3$, $CaCO_3$ and loss on ignition (see detailed description supra.)

Total Sulfate Analysis - Standard gravimetric procedure for total sulfate measurements. Ref. Scott's Standard Methods of Chemical Analysis.

Total Calcium and Magnesium Content - Normal atomic absorbtion procedure using a Jerrell Ash 850 AA instrument

Alkalinity Determination - Conducted as per Thiocyanate-Ferric Alum (volhard method) procedure outlined in Standard Methods of Water and Wastewater Analysis

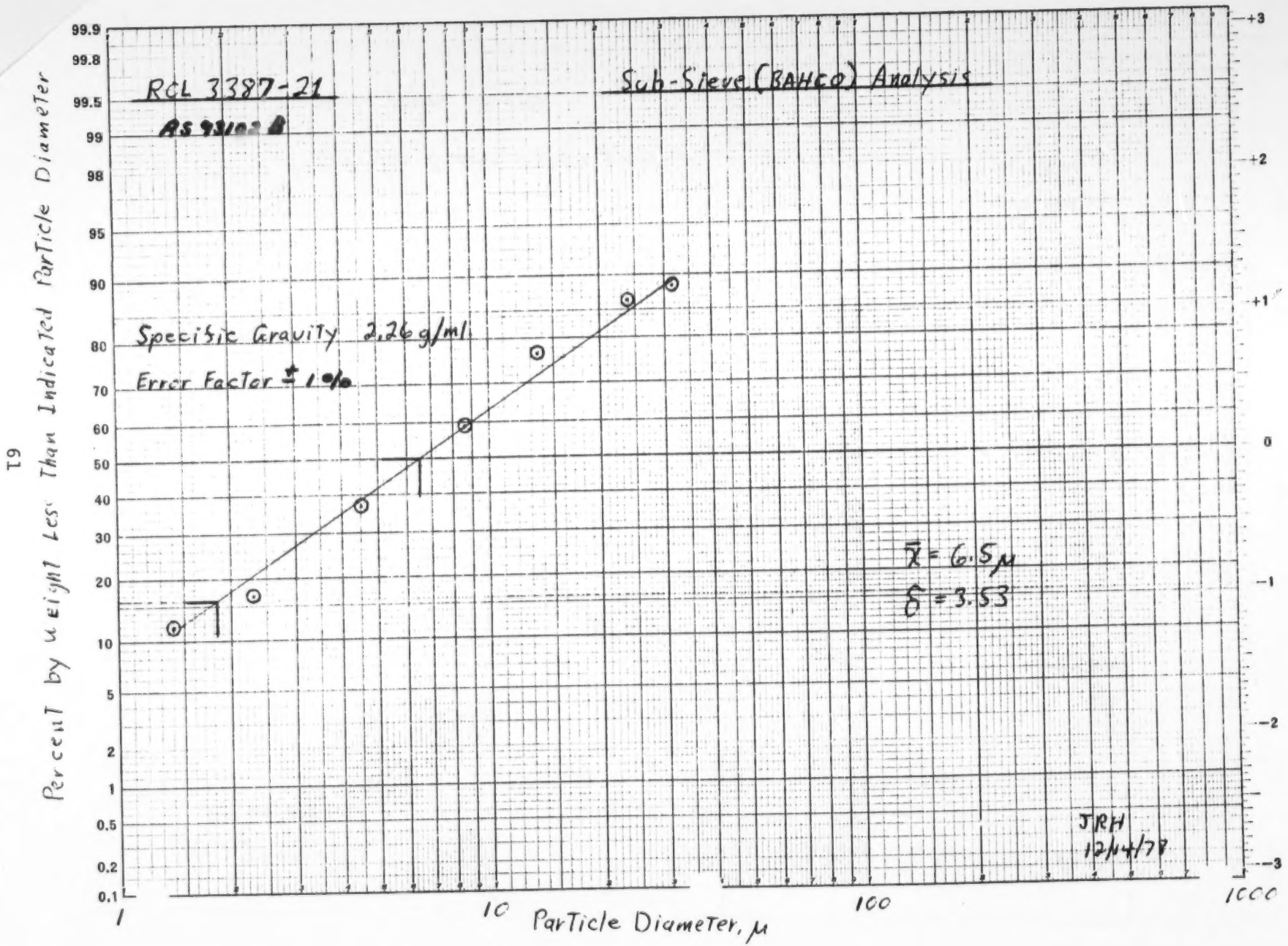
Coal Analysis - Methods as per those specified by U.S. Bureau of Mines publication PB-209-036. Instrumentation used for various tests are as follows:

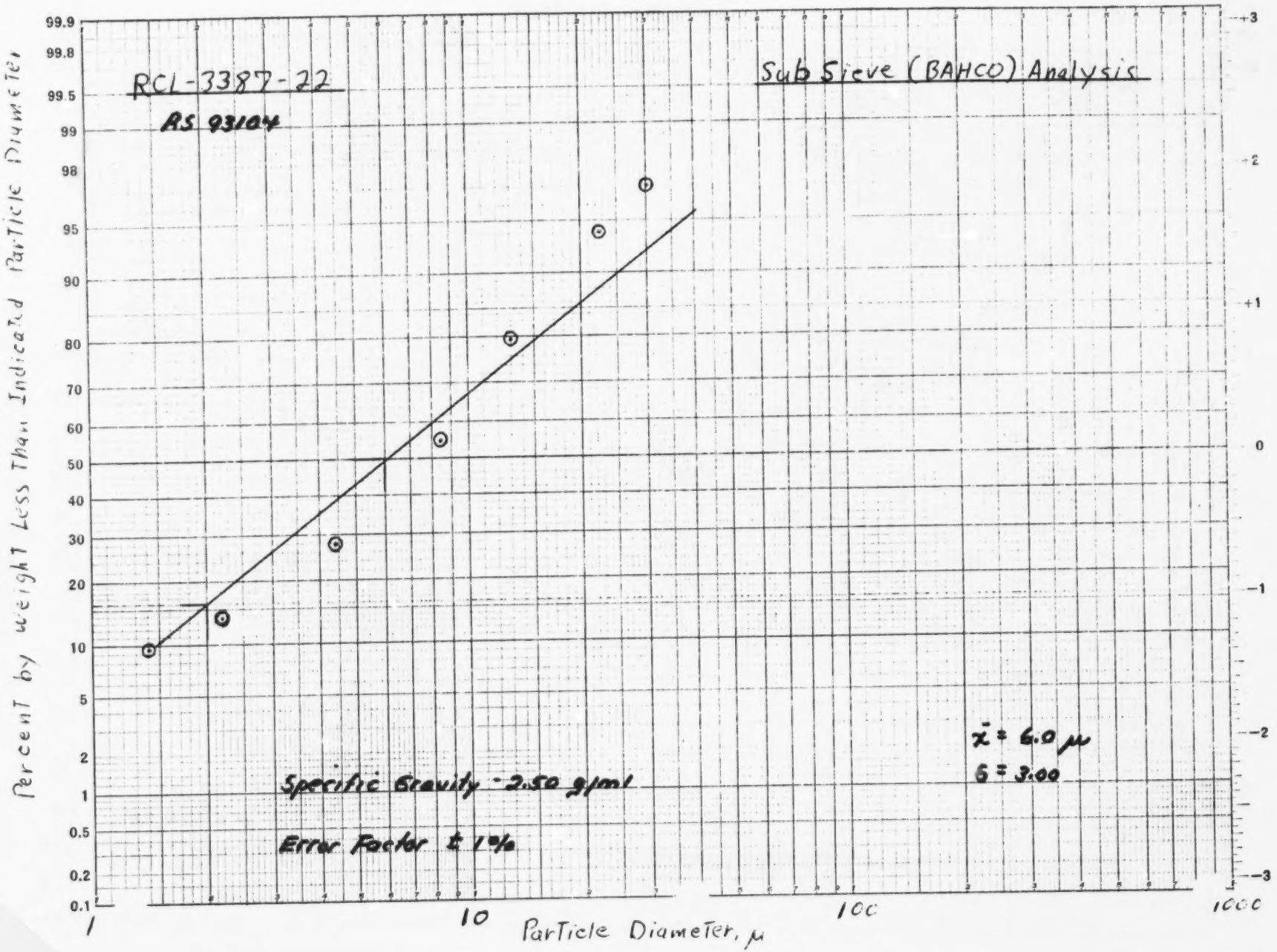
Percent Sulfur in coal - Leco Sulfur Analyzer
B.T.U. Values - Parr Calorimeter
Percent Carbon, Hydrogen, Nitrogen, - Perkin Elmer 240-Analyzer

Trace Elemental Analysis - Methods used to determine concentrations of Hg, Cd, Pb and Cr were derived from Varian Techtron publication 85-100224-00 and Jerrell Ash reference material dealing with flameless Atomic Absorption Spectroscopy. Methods from these sources were employed in conjunction with a Model 850 Jerrell Ash Atomic Absorption Spectrophotometer

APPENDIX C

SCRUBBER TEST DATA


RCL 3387-21
Sub-Sieve (BAHCO) Analysis
Specific Gravity 2.26 g/ml
Error Factor ± 1%
$\bar{x}$ = 6.5 μ
$\hat{\sigma}$ = 3.53
JRH
12/14/78
Percent by weight Less Than Indicated Particle Diameter
Particle Diameter, μ
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
+3
+2
+1
0
-1
-2
-3
1
10
100
1000


RCL-3387-22
RS 93104
Sub Sieve (BAHCO) Analysis
Specific Gravity - 2.50 g/ml
Error Factor ± 1%
$\bar{x}$ = 6.0 μ
δ = 3.00
Percent by weight Less Than Indicated Particle Diameter
Particle Diameter, μ
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
1
10
100
1000
+3
+2
+1
0
−1
−2
−3

SCRUBBER TEST DATA

Date	Time	Scrubber Inlet Temp. °F	Scrubber Inlet Temp. °C	GAS Flow To Scrubber SCFM	GAS Flow To Scrubber NM^3/hr	Lime Sludge pH	Scrubber ph	Dissolver pH	Scrubber Slurry S.G.	Lime Sludge S.G.	Scrubber SO_2 Concentration PPM Inlet	Scrubber SO_2 Concentration PPM Outlet
11/1/78	4:00	300		44,000		10.7	6.0	6.2	1.09	1.31	315	73
11/1/78	8:00	325		44,000		10.7	6.0	6.0	1.09	1.3	327	115
11/1/78	0:10	315		45,000		10.7	6.4	6.15	1.093	1.276	378	57
10/31/78	15:40	300		45,000		10.7	6.1	6.3	1.075	1.085	345	63
10/31/78	20:00	300		45,000		10.3	6.3	6.45	1.082	1.262	450	66
10/31/78	11:40	325		44,000		10.6	5.95	6.25	1.089	1.32	384	84
10/31/78	8:40	348		41,050		10.6	5.9	6.1	1.090	1.21	400	91
10/31/78	4:10	315		37,000		10.7	6.0	6.4	1.090	1.25	386	77
10/31/78	0:10	330		33,000		10.7	5.9	6.15	1.075	1.28	450	67
10/30/78	20:00	320		38,000		10.7	6.1	6.2	1.109	-	423	70
10/30/78	16:00	305		40,000		-	5.95	6.1	1.085	1.31	333	51
10/30/78	12:00	338		37,500		10.7	6.0	6.2	1.077	1.047	400	83
10/30/78	6:10	340		27,000		-	3.5	4.8	1.115	1.26	346	156
10/30/78	2:10	330		27,000		10.7	4.8	5.3	1.085	1.26	347	143
10/29/78	22:10	340		32,000		10.5	3.7	4.4	1.077	1.29	459	169
10/29/78	2:10	342		37,000		10.5	4.9	4.8	1.105	1.015	435	161
10/29/78	18:10	-		43,000		10.6	4.0	4.6	1.074	1.204	431	145
10/29/78	14:10	325		44,500		10.4	3.4	4.35	1.070	1.336	440	196
10/29/78	Day Shift	330		44,000		10.7	4.4	5.1	1.07	1.12	606	222
10/29/78	6:10	340		38,000		10.6	4.5	4.5	1.10	1.064	555	208
10/28/78	19:10	300		45,000		-	4.9	4.2	1.082	1.05	541	169
10/28/78	23:10	330		-		10.6	4.9	4.4	1.078	1.070	556	182

pH

Identification No. CES-355

RESEARCH-COTTRELL, INC.

RCL No. 3387

Coal Analysis Report

RCL No	Tech. Dept No.	Sample Date	Sample Identification and Description: Coal Mine Name and Location	Sample Identification and Description: Source/Type Sample	Unit	Station
1	10291410 C	10/29/78	2:10 P.M.	Coal		
2	10312000 C	10/31/78	8:00 P.M.	Coal		
3						
4						
5						
6						

RCL No	Proximate Analysis (As Rec'd Basis): % Moisture	% Ash	% Sulfur	% Vol. Mat	% Fixed	Btu	Ultimate Analysis (As Rec'd Basis): %C	%H	% N	% S	% O_2	% CL^-			Sulfur Forms (As Rec'd Basis): % Pyritic	% Sulfate	% Organic (by-Diff.)
1	6.26	11.0	2.66				63.62	4.56	1.25	2.66	10.75						
2	8.27	9.81	1.95				63.33	4.36	1.20	1.95	11.08						
3																	
4																	
5																	
6																	

RCL No	Mineral Analysis of Dry Ash (%): SiO	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	Other		Undeter.	Total	Comments or Special Analysis
1															
2															
3															
4															
5															
6															

RC 1074

APPENDIX D

Water Plant Survey Data

Identification No CES 355

RESEARCH-COTTRELL, INC

RCL No 3387

Fly Ash Particle Size Report

			Sample Identification and Description			
RCL No	Tech Dept No	Sample Date	Coal Mine - Name and Location	Utility - Station, Unit	Source/Type	Date/Initials
18	RS 93108					
20	RS 93102 A					
21	RS 93102 B					
22	RS 93104					
37						
38						

Density Analysis **Sieve Analysis**

	Specific Gravity	Bulk Density		% Finer Than					Comments
RCL No	gms/cc	Compact (lbs/ft³)	Uncomp (lbs/ft³)	44 µm	74 µm	149 µm	297 µm	+ 297 µm	
18	2.34								
20	2.45								
21	2.26								
22	2.50								
37	2.33								
38	2.55								

Sub-Sieve (Bahco) Analysis

	Percent By Weight Less Than Indicated Particle Diameter																Statistical Data	
RCL No	µm	%	µm	%	µm	%	µm	%	µm	%	µm	%	µm	%	>µm	%	Mass Median $\bar{X}$	Std Dev
18	1.4	3.39	2.3	8.15	4.5	20.77	8.4	31.37	13.4	41.04	23.4	51.15	31.0	54.82	31.0	45.18		
20	1.4	2.89	2.2	7.30	4.4	26.32	8.3	61.43	13.1	91.61	22.9	98.68	30.3	99.42	30.3	0.58		
21	1.4	11.80	2.3	16.87	4.5	36.57	8.6	58.57	13.6	76.56	23.8	86.30	31.5	88.50	31.5	11.50		
22	1.4	9.64	2.2	13.51	4.4	27.79	8.2	54.68	13.0	79.71	22.6	94.11	30.0	97.01	30.0	2.99		
37	1.4	28.19	2.3	51.39	4.5	58.50	8.5	65.36	13.4	68.13	23.5	70.22	31.1	71.34	31.1	19.17		
38	1.4	2.76	2.2	10.42	4.4	44.02	8.1	78.33	12.9	92.40	22.4	94.22	29.7	94.46	29.7	0.32		

RC 1073

Identification No CES-355

RESEARCH-COTTRELL, INC.

RCL No. 3387

Fly Ash Particle Size Report

RCL No	Tech. Dept. No.	Sample Date	Sample Identification and Description: Coal Mine - Name and Location	Sample Identification and Description: Utility - Station, Unit	Source/Type	Date/Initials
12	RS 93110					
13	RS 93116					
14	RAFB 1					
15	RAFB 2					
16	RS 93106					
17	RS 93107					

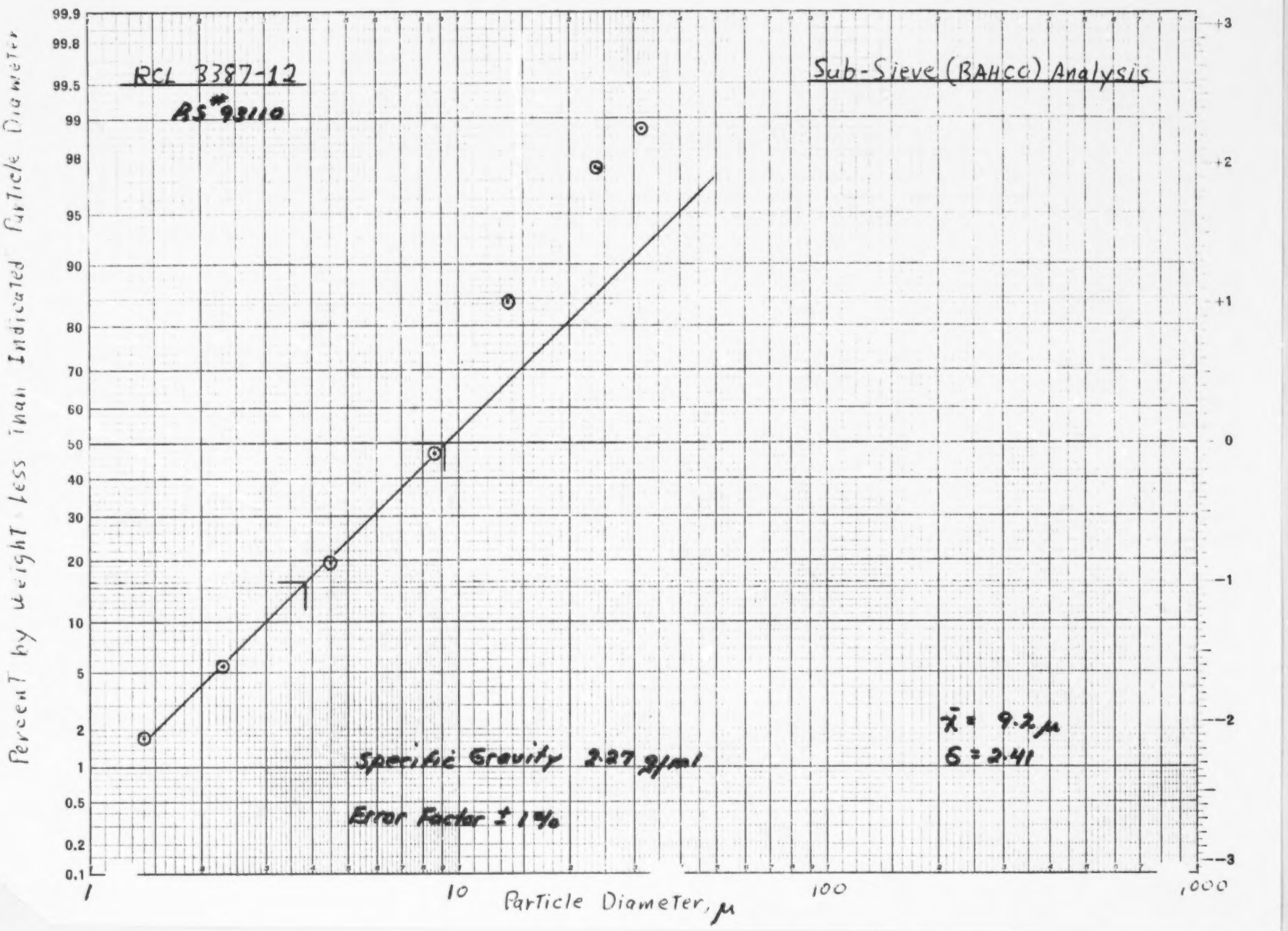
Density Analysis / Sieve Analysis

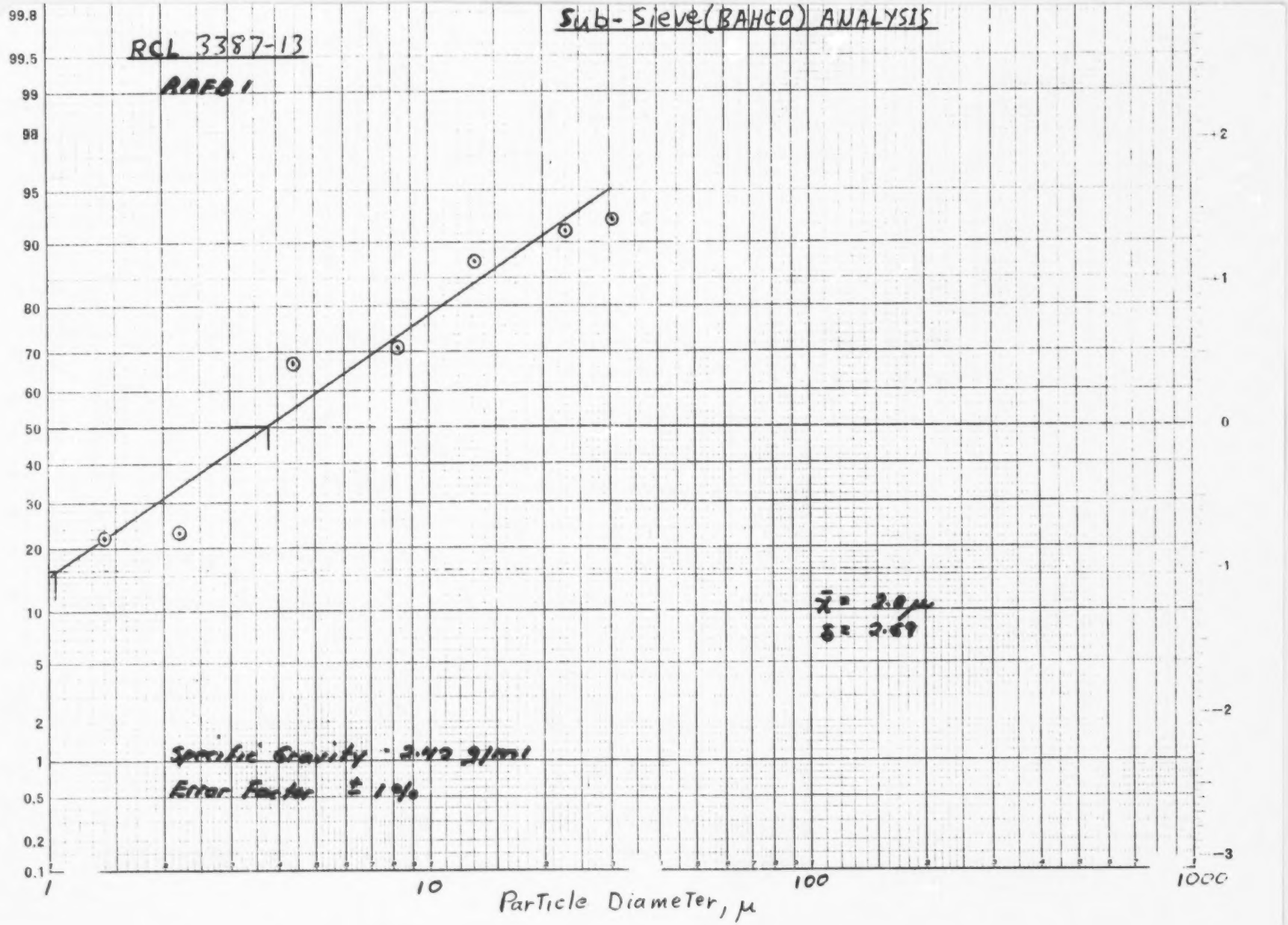
RCL No	Specific Gravity gms/cc	Bulk Density: Compact (lbs/ft³)	Bulk Density: Uncomp. (lbs/ft³)	% Finer Than: 44 µm	74 µm	149 µm	297 µm	+ 297 µm	Comments
12	2.27								
13	2.42								
14	2.13								
15	1.96								
16	2.28								
17	2.46								

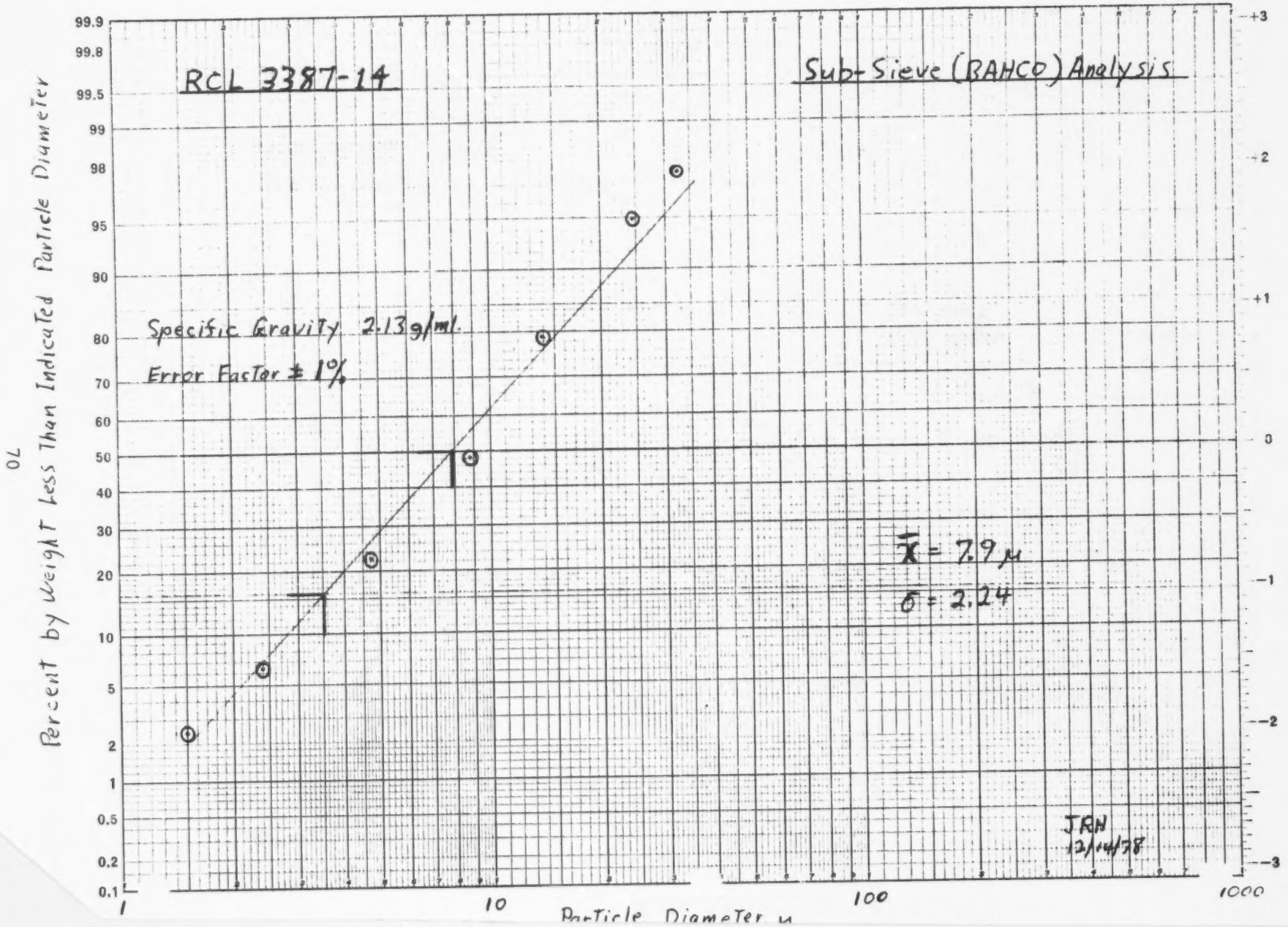
Sub-Sieve (Bahco) Analysis

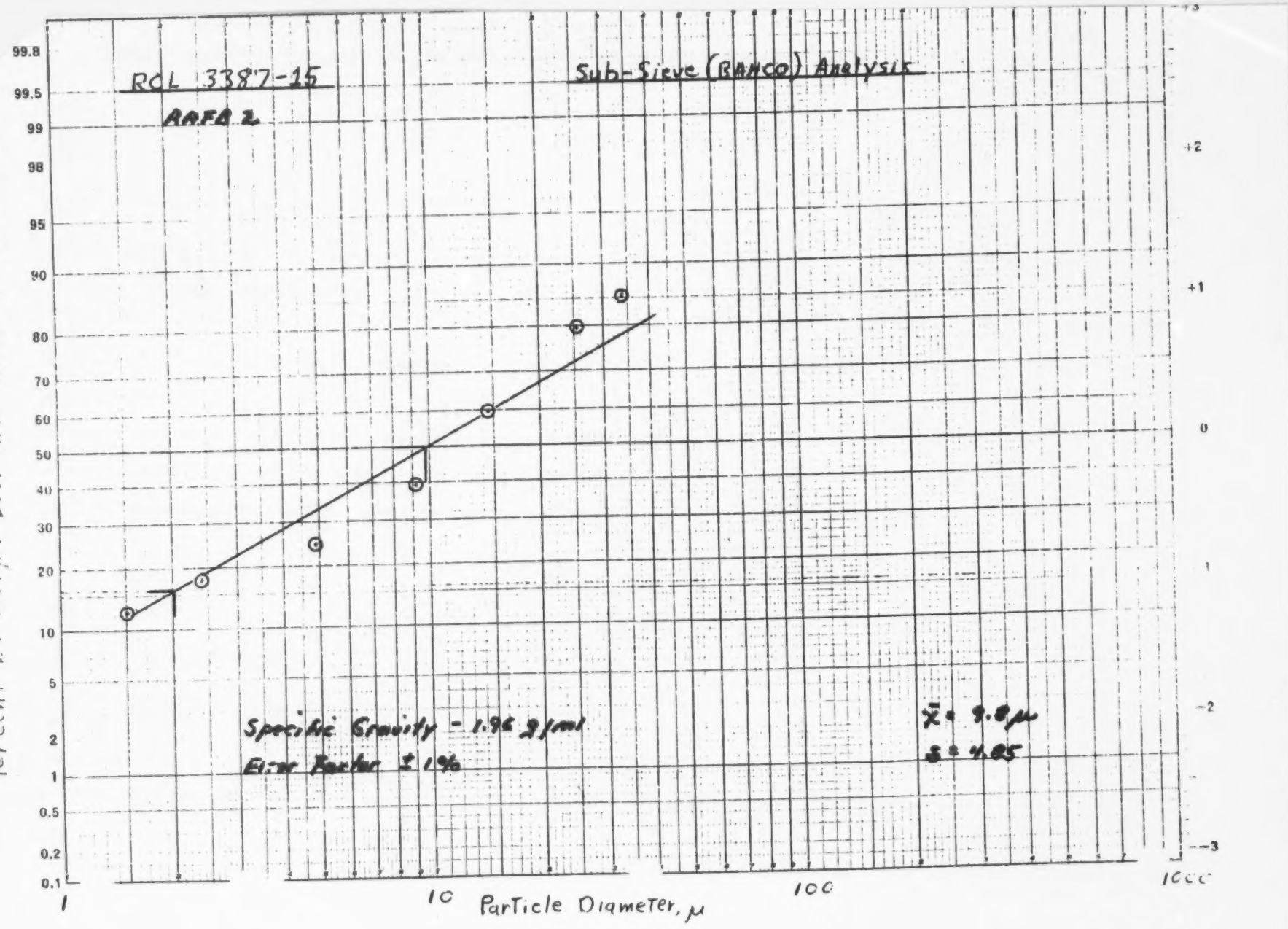
RCL No	Percent By Weight Less Than Indicated Particle Diameter: µm	%	µm	%	µm	%	µm	%	µm	%	µm	%	µm	%	>µm	%	Statistical Data: Mass Median $\bar{X}$	Std. Dev
12	1.4	1.75	2.3	5.53	4.5	19.62	8.6	47.00	13.6	84.51	23.7	97.71	31.5	98.80	31.5	1.20		
13	1.4	22.03	2.2	23.77	4.4	67.86	8.3	71.00	13.2	87.63	23.0	91.15	30.5	92.31	30.5	7.69		
14	1.5	2.47	2.4	6.25	4.7	22.69	8.8	48.21	13.9	78.92	24.4	94.93	32.4	97.58	32.4	2.42		
15	1.5	12.41	2.4	17.53	4.9	24.56	9.2	39.71	14.5	59.90	25.4	79.52	33.8	85.27	33.8	14.73		
16	1.4	9.48	2.3	16.51	4.5	31.48	8.5	44.84	13.6	57.57	23.7	70.49	31.4	75.03	31.4	23.09		
17	1.4	2.05	2.2	7.81	4.4	28.23	8.2	62.00	13.1	89.20	22.8	98.26	30.2	98.85	30.2	1.15		

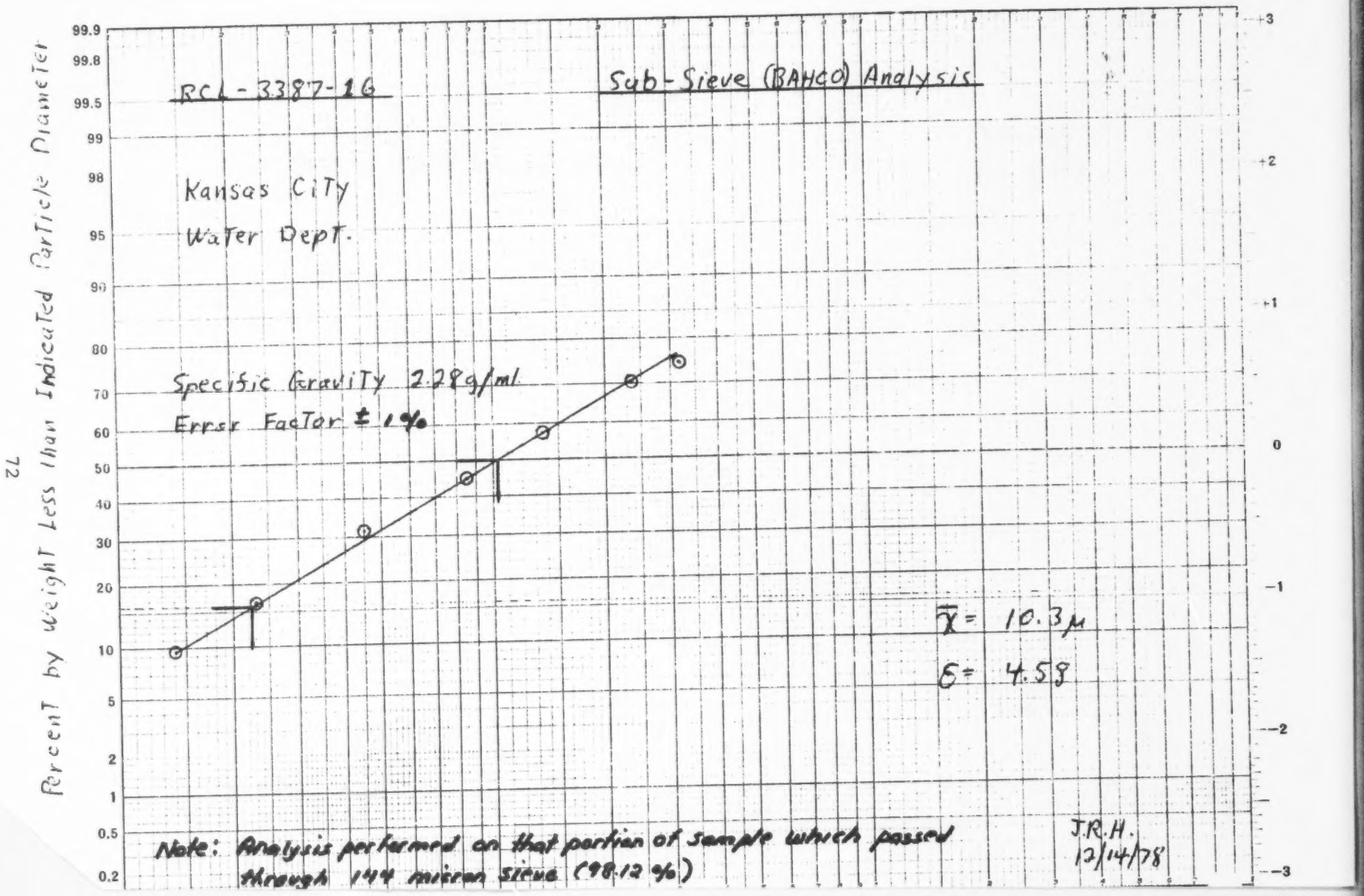
RC 1073

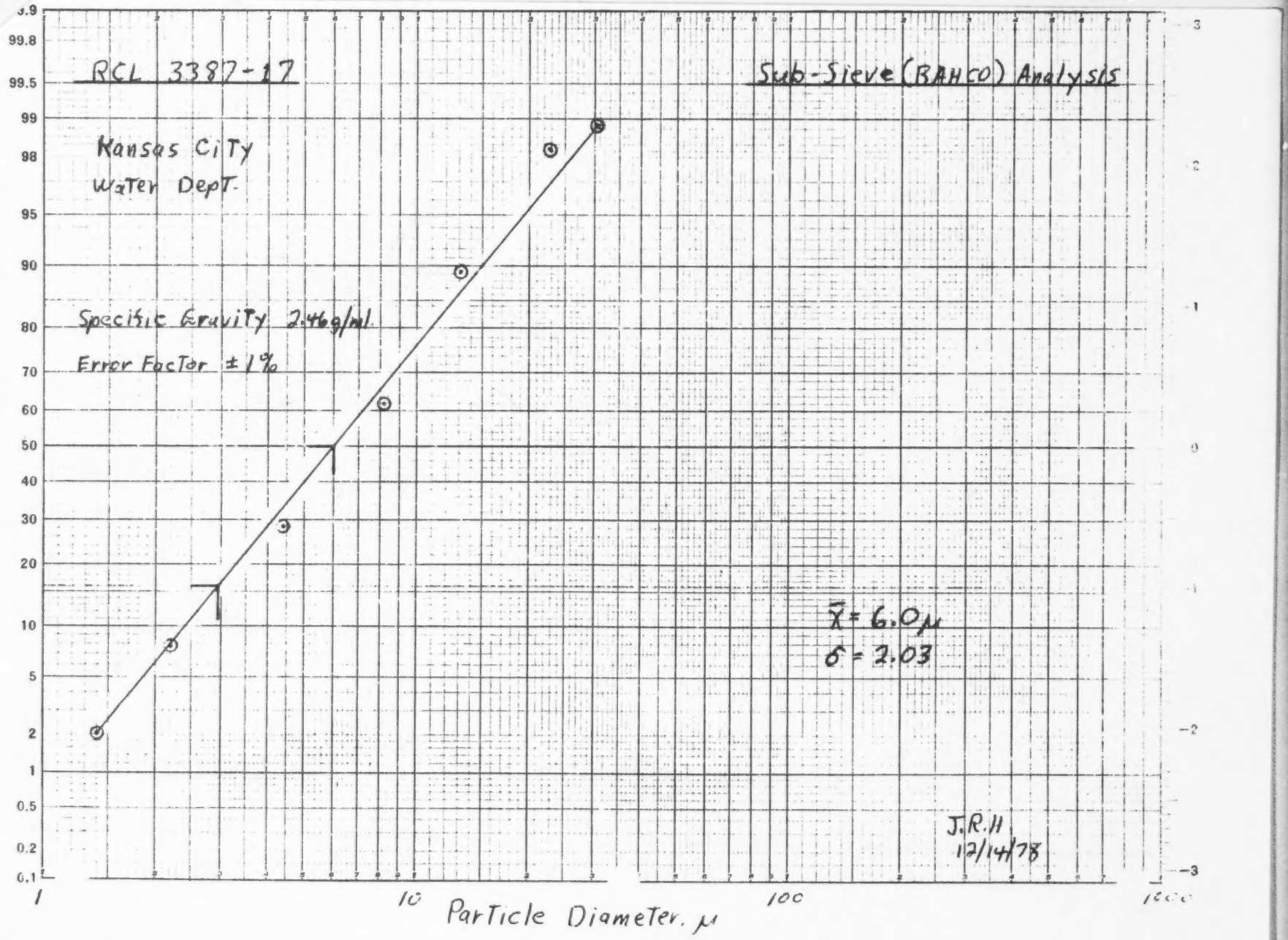

RCL 3387-12
BS# 93110
Sub-Sieve (BAHCO) Analysis
Specific Gravity 2.27 g/ml
Error Factor ± 1%
$\bar{x}$ = 9.2 μ
δ = 2.41
Percent by weight less than Indicated Particle Diameter
Particle Diameter, μ
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
+3
+2
+1
0
−1
−2
−3
1
10
100
1000


Sub-Sieve (BAHCO) ANALYSIS
RCL 3387-13
AAFB 1
Per cent by weight Less Than indicated Particle Diam.
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
+2
+1
0
-1
-2
-3
$\bar{x}$ = 2.0 μ
s = 2.69
Specific Gravity - 2.42 g/ml
Error Factor ± 1%
1
10
100
1000
Particle Diameter, μ


RCL 3387-14
Sub-Sieve (BAHCO) Analysis
Specific Gravity 2.13 g/ml.
Error Factor ± 1%
$\bar{x}$ = 7.9 μ
σ = 2.24
JRN
12/14/78
Percent by Weight Less Than Indicated Particle Diameter
Particle Diameter μ
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
1
10
100
1000
+3
+2
+1
0
−1
−2
−3


RCL 3387-15
AAFA 2
Sub-Sieve (RANCO) Analysis
Specific Gravity - 1.96 g/ml
Elut Factor ± 1%
$\bar{X}$ = 9.8 μ
S = 4.85
Percent by Weight Less Than Indicated Particle Diameter
Particle Diameter, μ
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
+3
+2
+1
0
1
−2
−3
1
10
100
1000


RCL-3387-16
Sub-Sieve (BAHCO) Analysis
Kansas City
Water Dept.
Specific Gravity 2.28g/ml
Error Factor ± 1%
$\bar{x}$ = 10.3μ
σ = 4.58
Note: Analysis performed on that portion of sample which passed through 144 micron sieve (98.12 %)
J.R.H.
12/14/78
Percent by Weight Less than Indicated Particle Diameter
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
+3
+2
+1
0
-1
-2
-3


RCL 3387-17
Sub-Sieve (BAHCO) Analysis
Kansas City
Water Dept.
Specific Gravity 2.46 g/ml
Error Factor ±1%
$\bar{X}$ = 6.0 μ
σ = 2.03
J.R.H
12/14/78
Percent by weight Less Than Indicated Particle Diameter
Particle Diameter, μ
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
1
10
100
3
2
1
0
-1
-2
-3

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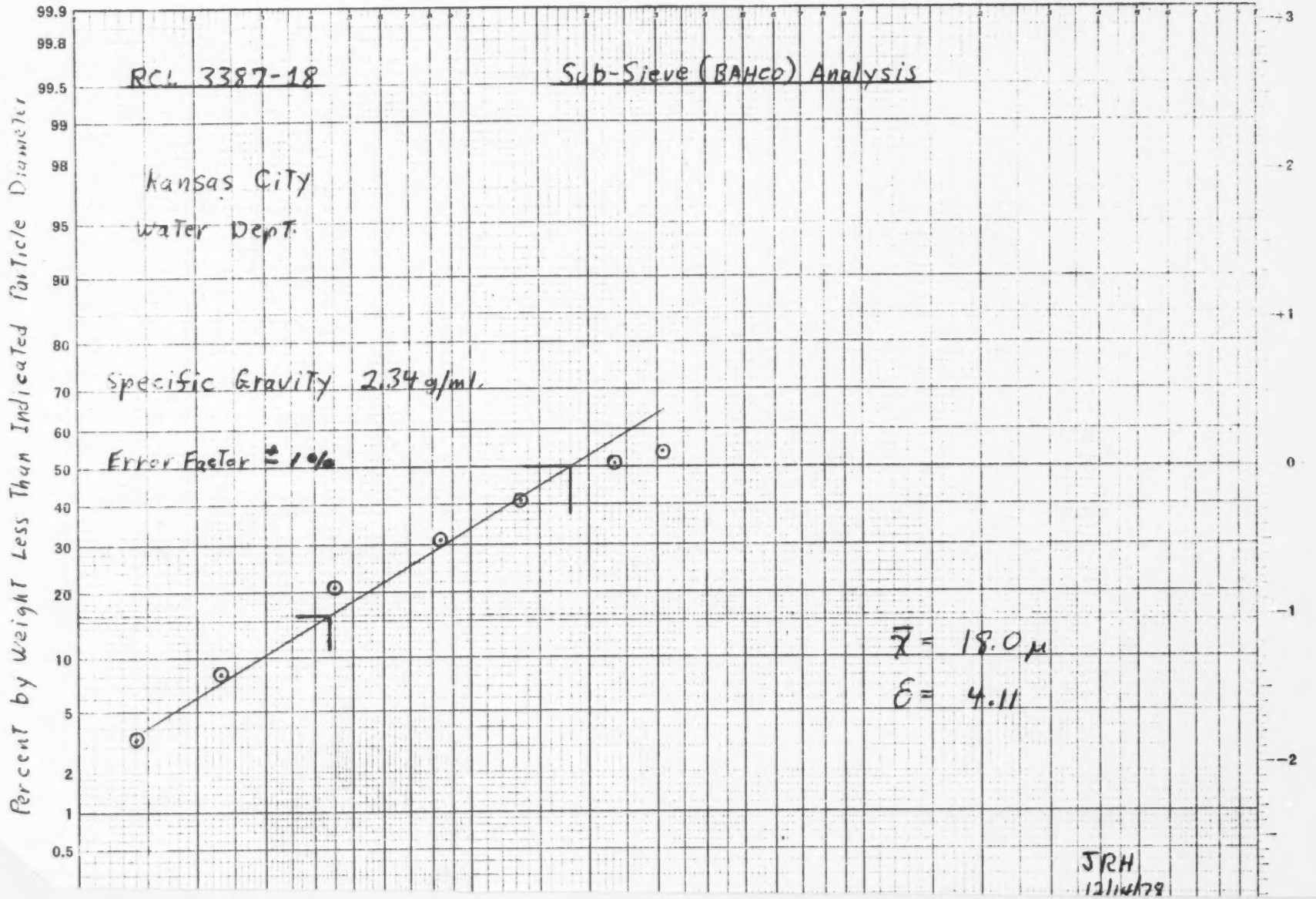
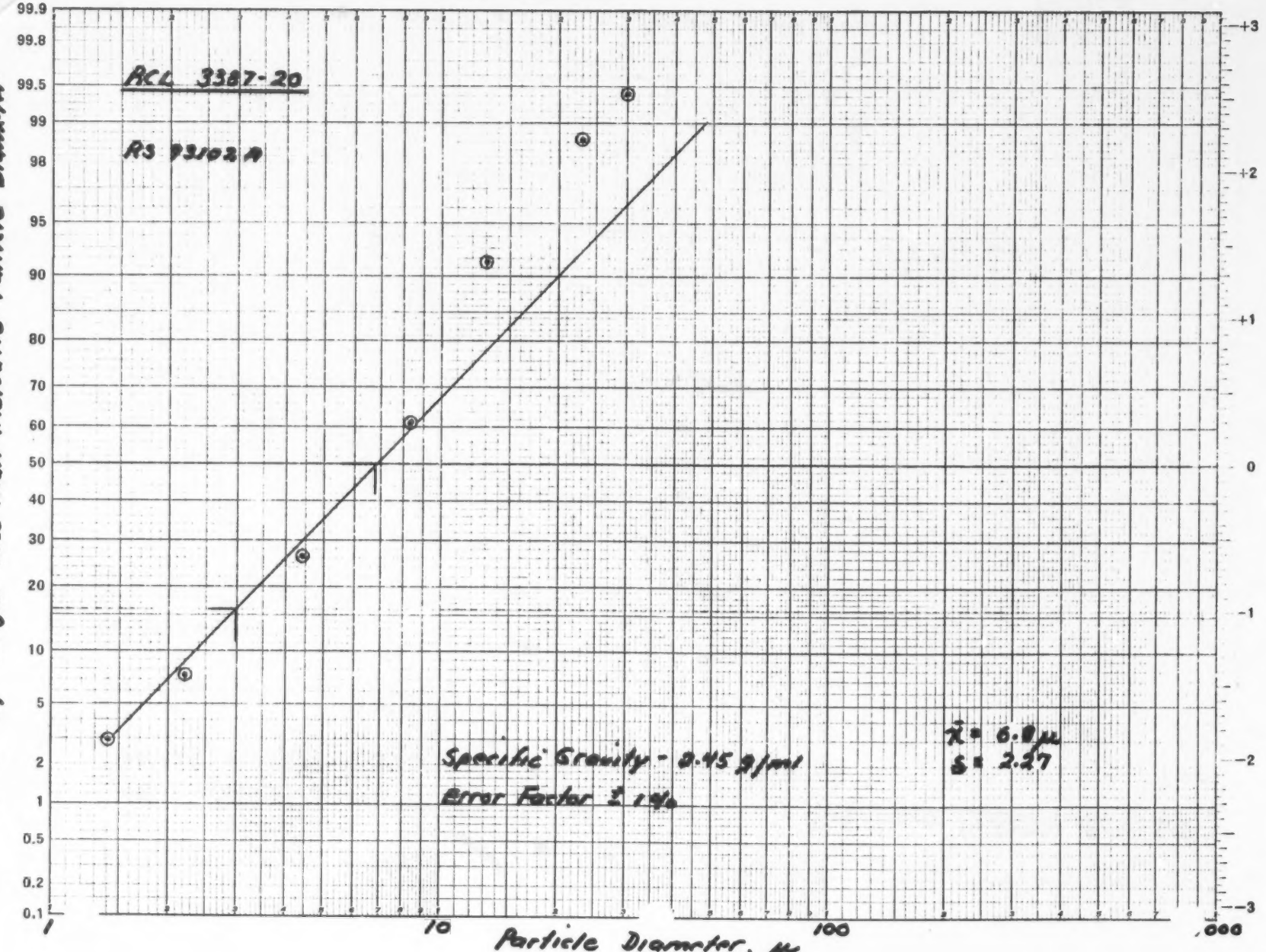
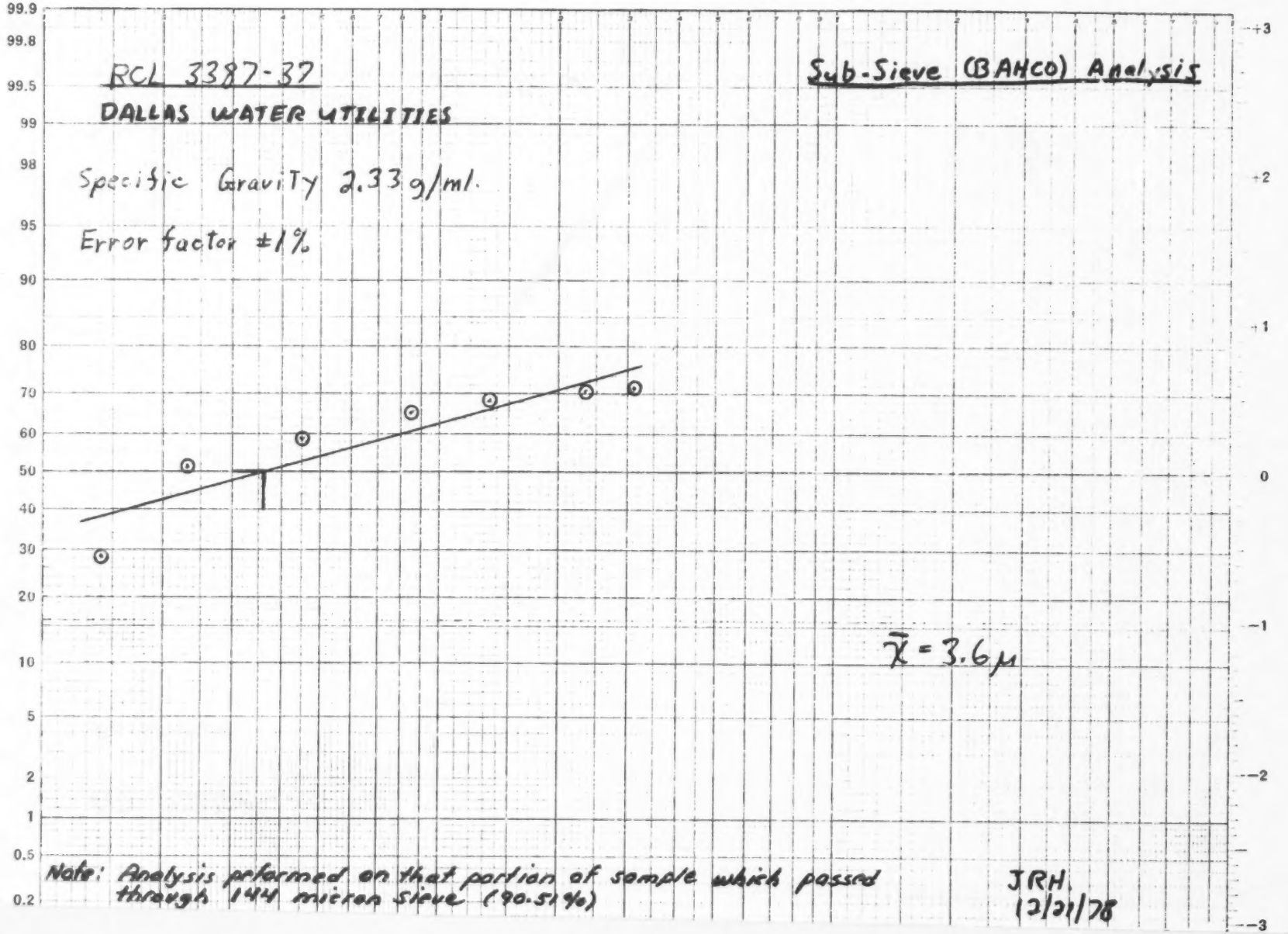
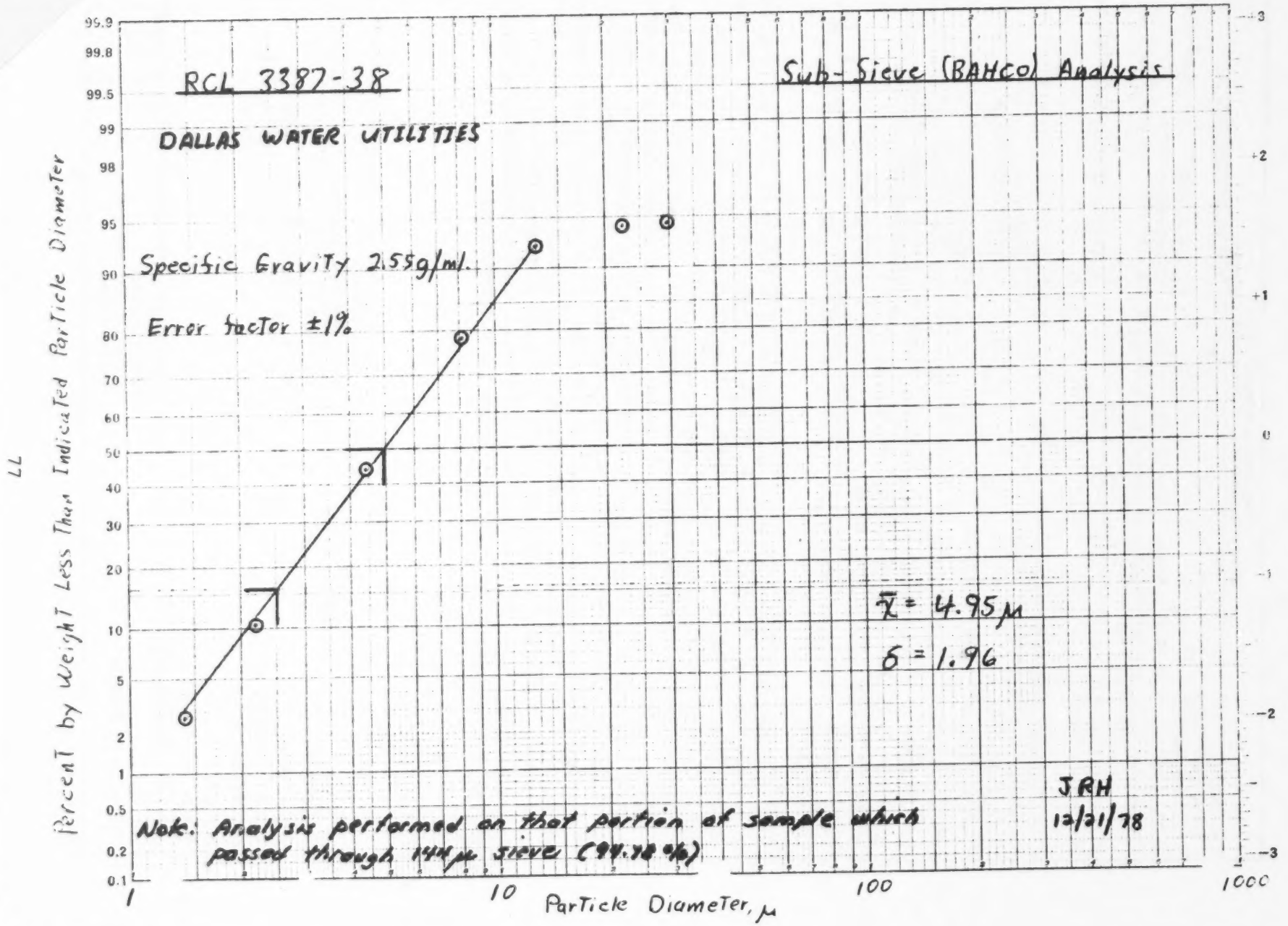



RCL 3387-20
RS 93102 A
Per Cent by Weight Less Than Indicated Particle Diameter
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
+3
+2
+1
0
-1
-2
-3
1
10
100
,000
Particle Diameter, μ
Specific Gravity - 0.45 g/ml
Error Factor ± 1%
x̄ = 6.8 μ
s = 2.27


RCL 3387-37
DALLAS WATER UTILITIES
Specific Gravity 2.33 g/ml.
Error factor ±1%
Sub-Sieve (BAHCO) Analysis
$\bar{x}$ = 3.6 μ
Note: Analysis performed on that portion of sample which passed through 1444 micron sieve (90.51%)
JRH
12/21/78
Percent by weight Less Than Indicated Particle Diameter
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
+3
+2
+1
0
-1
-2
-3


RCL 3387-38
Sub-Sieve (BAHCO) Analysis
DALLAS WATER UTILITIES
Specific Gravity 2.55g/ml.
Error factor ±1%
$\bar{x}$ = 4.95 μ
σ = 1.96
JRH
12/21/78
Note: Analysis performed on that portion of sample which passed through 149 μ sieve (99.98 %)
Percent by Weight Less Than Indicated Particle Diameter
Particle Diameter, μ
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
1
10
100
1000
+3
+2
+1
0
-1
-2
-3